Environmental Controls on Clogging in Effluent-Dominated Waterways

by

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ABSTRACT

The Santa Cruz River, in southern Arizona, receives steady inputs of nutrient-enriched treated wastewater (effluent). Previous studies have documented reduced infiltration of surface water in the river. This disruption of hydrologic connectivity, or clogging, can have consequences for groundwater recharge, flows of wastewater in unwanted locations, and potentially even survivorship of floodplain riparian vegetation. Clogging can result from biotic processes (microbial or algal growth), abiotic processes (siltation of interstitial spaces), or both. Little is known about clogging in rivers and the environmental factors that regulate their dynamics, so natural field experiments along the Santa Cruz and San Pedro Rivers were used to answer: 1) Are there spatial patterns of hydraulic conductivity in the riverbed downstream from the effluent point-source? 2) Is there temporal variability in hydraulic conductivity and microbial abundance associated with flooding? 3) Are there environmental variables, such as nutrients or stream flow, related to differences in hydraulic conductivity and microbial abundance? To address these questions, a series of sites at increasing distance from two municipal effluent discharge points with differing water quality were selected on the Santa Cruz River and compared with non-effluent control reaches of the San Pedro River. Physical, chemical, and biological parameters were monitored over one year to capture seasonal changes and flood cycles.

An additional site on the Santa Cruz was established with the Bureau of Reclamation to determine the effects of drying on surface water infiltration. Results revealed trends of increasing conductivity with distance from the effluent discharge for both reaches. Conductivity on the low-nutrient reach was 1.4-3.1 times higher than the high-nutrient reach. Floods restored conductivity rates of the river banks, while in the absence of flooding, conductivity rates gradually declined to clogged conditions. Areas of low conductivity were associated with higher fine sediments and microbial counts, and lower nitrates. This study concludes that utilizing higher-quality effluent is sufficient to reduce clogging. However, even with improved water quality, the absence of scouring flows still leads to lower conductivity rates. Management strategies for effluent, riverbed groundwater recharge, and maintaining valued riparian corridors should include maintaining higher water quality and scouring flows.

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TABLE OF CONTENTS

Page

LIST OF TABLES vii

LIST OF FIGURES ix

CHAPTER

1. A search for Patterns and variables of riverbed clogging 1

Introduction 1

Study Area And Experimental Design 8

Methods 11

Saturated hydraulic conductivity 11

Characterization of sediments and environmental variables 13

Analysis 17

Results 17

Are there spatial patterns of hydraulic conductivity associated with effluent? 18

Is there temporal variability in hydraulic conductivity and microbial abundance in response to flooding? 19

Are there environmental variables, such as nutrients or stream flow, related to differences in hydraulic conductivity and microbial abundance? 21

CHAPTER Page

Discussion 29

Are there spatial patterns of hydraulic conductivity associated with effluent? 29

Is there temporal variability in hydraulic conductivity and microbial abundance in response to flooding? 32

Are there environmental variables, such as nutrients or stream flow, related to differences in hydraulic conductivity and microbial abundance? 34

Conclusions 40

2. BALANCING CLOGGING WITH ENHANCED RECHARGE 65

Introduction 65

Study Area 67

Methods 68

Hydrology 68

Sediment characterization 69

Water chemistry 71

Analysis 72

Results 73

Did hydraulic conductivity change over time with treatment? 73

Page

Did sediment biomass change over time with treatment? 74

Were there trends in physiochemical parameters? 75

Discussion 77

Did hydraulic conductivity change over time with treatment? 77

Did sediment biomass change over time with treatment? 78

Were there trends in physiochemical parameters? 81

Conclusions 84

References 94

APPENDIX

A HETEROTROPHIC PLATE COUNTS 103

B HYDRAULIC CONDUCTIVITY OF SEDIMENTS BY DEPTH.......... 104

C HYDRAULIC CONDUCTIVITY 110

D SEDIMENT TEXTURE ANALYSIS 116

LIST OF TABLES

Table Page

1. Requirements for Class A+ and B effluent 46

2. Spearman's rho values measuring correlation between hydraulic conductivity, microbial counts, and environmental variables from the Santa Cruz and San Pedro Rivers 53

3. Pearson's correlation coefficients for hydraulic conductivity, microbial counts, and fines on the Enhanced Recharge Project 92

4. Water chemistry from the Enhanced Recharge Project 93

LIST OF FIGURES

Figure Page

1. Aerial view of tree die-off 42

2. Detail of clogging 43

3. Conceptual model of clogging in an effluent-dominated waterway.. 44

4. Map of study sites on the Santa Cruz and San Pedro Rivers 45

5. Examples of sediment cores 47

6. Hydraulic conductivity of Santa Cruz and San Pedro Rivers 48

7. Stream discharge on the Lower Santa Cruz River during study period and 2 years prior 49

8. Stream discharge on the Upper Santa Cruz River during study period and 2 years prior 50

9. Stream discharge on the San Pedro River during study period and 95 years prior 51

10. Heterotrophic plate counts from the Santa Cruz and San Pedro Rivers 52

11. Fine sediments concentrations on the Santa Cruz and San Pedro Rivers 54

12. Ammonia concentrations on the Santa Cruz and San Pedro Rivers 55

13. Nitrate-nitrite concentrations on the Santa Cruz and San Pedro Rivers 56

Figure Page

14. Total Phosphorous concentrations on the Santa Cruz and San Pedro Rivers 57

15. Organic carbon concentrations on the Santa Cruz and San Pedro Rivers 58

16. Nutrient removal efficiency on the Santa Cruz River 59

17. Temperature on the Santa Cruz and San Pedro Rivers 60

18. Dissolved Oxygen concentrations on the Santa Cruz and San Pedro Rivers 61

19. pH on the Santa Cruz and San Pedro Rivers 62

20. ORP on the Santa Cruz and San Pedro Rivers 63

21. Stream discharge at study sites on the Santa Cruz and San Pedro Rivers 64

22. Study area of the Enhanced Recharge Project 86

23. Hydraulic conductivity of the Enhanced Recharge Project 87

24. Hydraulic conductivity by depth of the Enhanced Recharge Project 88

25. Heterotrophic plate counts from the Enhanced Recharge Project 89

26. Sediment texture of the Enhanced Recharge Project 90

27. Disolved oxygen and stream discharge of the Enhanced Recharge Project 91

1. A SEARCH FOR PATTERNS AND VARIABLES OF RIVERBED CLOGGING

Introduction

In arid regions, such as the southwestern U.S., water availability is always a matter of concern. While potable water sources like groundwater and surface waters decrease with urban development, our wastewater is a source that increases. Treating wastewater back to a potable stage is a prohibitively expensive process, so instead, this water is used for irrigation, recharge projects, and cooling towers. Water managers have been recharging treated wastewater to aquifers for some time now, and in drought-prone areas, recharge can be a critical, or even mandatory, part of sustainable water use. The Santa Cruz River in southern Arizona has been part of the story of a changing water supply. This river is unique in that it is the only one to cross the US border twice, as it dips into Mexico before returning north. It is also unusual because today most of its surface flow is fed by treated wastewater, or effluent, year-round. In fact, without the addition of effluent, approximately 52km (or 18%) of the river would be dry (Sonoran Institute, 2012). This was not always the case - during the late nineteenth century, climactic factors and human alteration of the channel started a decline in the length of perennial flow, which was later hastened by heavy groundwater pumping (Logan, 2002). Though there have been clear benefits to restoring perennial surface flow for the riparian vegetation and the wildlife that use the river as a migratory corridor, the costs of using water of impaired quality are not always clear.

One potential effect of adding effluent to the river is reduced infiltration of surface water via clogging of the channel sediments. On the Santa Cruz River, several researchers have documented areas of low infiltration, unsaturated sediments, and “schmutzdecke” (black anaerobic layers) (Galyean, 1996; Lacher, 1996; Treese et al., 2009). Lacher (1996) describes the perennial flow of the Santa Cruz near Tucson as being around 40km long in the absence of storms, but only 6 km long during storm periods. This contrary relationship can be explained by scouring action of storm flows disrupting clogged sediments and allowing surface water to permeate through the sediments. Another observation, likely related, is a wide-scale, multi-species tree die-off near the river in 2005 (Figure 1). While no single cause was implicated in the die-off, long-term drought and lack of scouring floods to scour the channel and recharge aquifer were determined to be the most likely culprits (McCoy, 2007). These observations and events led us to question the exact nature of the clogging layer, where and when it occurs, and what factors regulate it.

The clogging process has not been well-studied under the flowing conditions of a river, but managers of artificial recharge basins and injection wells routinely deal with clogging issues (Baveye et al., 1998; Bouwer 2002, and references therein). Recharging water through porous media is dependent on free movement of the water to the aquifer. However, pore spaces can be easily blocked and when this occurs, infiltration slows and must be restored. In recharge ponds, clogging is controlled by letting the pond dry and scraping or tilling the sediments with heavy machinery. In recharge wells, backwashing helps restore flow (Bouwer, 2002).

Clogging can result from biotic processes (microbial or algal growth), abiotic processes (siltation of interstitial spaces in the channel bed), or both (Vandevivere & Baveye, 1992b) (Figure 2). Physical clogging, or colmation, occurs when suspended particles in the water are strained through sediments and become lodged in the interstitial pore spaces (Brunke, 1999). Much like plaque in an artery that reduces blood flow, infiltration rates of water decline as more pore spaces become clogged. In this case, the size of the pore spaces is important, as smaller pores will be more prone to clogging. The type of sediments found in a river, and how they are packed, will affect the rate of clogging. Smaller, fine particles, such as clay and silt, pack together tightly and leave small interstitial pores. Larger-grained sediments like coarse sand and cobble pack in a way that leaves larger pore networks. Biotic interactions can influence this process; dense growth of macrophytes may enhance accumulation of fine sediments (Wharton et al., 2006), as can biofilms produced by microorganisms (Vandevivere & Baveye, 1992a; de Lozada et al., 1994; Wharton et al., 2006).

Biological clogging is caused by direct and indirect effects of microorganisms (algae and bacteria). These effects include the buildup of cell biomass, extracellular polysaccharides (biofilms), and metabolic waste products like nitrogen gas. Any surface that is regularly exposed to water, such as saturated sediments in rivers, contains microorganisms growing in biofilms. Biofilms are multi-species aggregations of bacteria and other microorganisms that have attached to a surface by building an extracellular polysaccharide matrix. Biofilms can quickly develop into a cooperative, complex microecosystem within which nutrients and organic matter can be stored, transformed, and released back to surface waters (Boulton et al., 1998). Biofilms can develop on the top layer of sediments in a river and be composed more of photosynthetic algae and cyanobacteria, but can also form deeper in the sediments, out of reach of sunlight, and be composed of heterotrophic microbes (Pusch et al., 1998). Biofilms can form continuous, impenetrable layers, or can form isolated microcolonies that fill interstitial spaces between the sediments (Baveye & Valocchi, 1989). In the case of the Santa Cruz River, a survey conducted by the AZ Department of Environmental Quality found that chlorophyll was low given the amount of nutrients available (<10mg/m^3 phytoplankton, <150 mg/m^2 periphyon) (Walker et al., 2005), indicating that heterotrophic biofilms might be predominant.

The composition, activity, and extent of a biofilm is influenced by environmental parameters such as dissolved oxygen, organic carbon, nutrients, and ions (Storey et al., 1999). These parameters, in turn, vary with the flow rates and flow paths of the surrounding water, which can be influenced by on-site biologic activities such as macrophyte growth in the streambed. Large floods of long duration can mobilize sediments and disrupt biofilms (Hancock & Boulton, 2005), and biofilms are also disrupted by extended drought. However, once river flow returns, the biofilm growth can rapidly redevelop (Eisenmann et al., 1999).

Biological clogging has been most studied in the laboratory. Under controlled conditions, flowing, sand-filled columns can be subjected to various treatments while monitoring changes in infiltration. Taylor and Jaffé (1990) conducted a similar experiment by inoculating sand columns with bacteria and a carbon source and found permeability was reduced by three orders of magnitude. In another column experiment using sterile deionized water, Gupta and Swartzendruber (1962) found that conductivity was not significantly reduced until bacterial numbers reached $4x10^5$ cells per gram of sand. However, Vandevivere and Baveye (1992a) found in their columns that even when bacterial numbers were too low to reduce infiltration, the exopolymer matrix produced by the bacteria was sufficient to cause clogging.

Though column studies have the benefit of isolating a few variables at a time, under natural conditions, a multitude of variables can influence biological clogging. Due to inherent difficulties, outdoor studies are less common, but similar results have been found under saturated, sandy conditions. Okubo and Matsumoto (1983) described bioclogging as "a major problem" when trying to recharge secondary effluent through sand. They determined that suspended solids and organic carbon had to be maintained at low concentrations to prevent clogging. Ehrlich and others (1979) injected tertiary-treated wastewater through a well into a medium-fine sandy aquifer, but had to maintain chlorine levels at 2.5 mg/L in order to keep microbial growth from clogging the well. Wood and Bassett (1975) monitored an artificial recharge basin and found that a strong decrease in infiltration rates corresponded with the growth of anaerobic bacteria.

In flowing systems, rivers receiving effluent can support greater microbial biomass. A study of an Italian river downstream of a municipal wastewater treatment plant found higher microbial biomass and respiration rates than the non-effluent reach upstream of the treatment plant (Ruggiero et al., 2006). Bioclogging is so readily induced that researchers are experimenting with adding nutrients to grow clogging layers in aquifers as biobarriers to prevent the migration of contaminants (Blowes et al., 2000; Hunter, 2001) or the loss of water (Ahmad et al., 1996).

Our current understanding of clogging forms the basis for the hypothesis of this study: that water quality in rivers receiving a constant supply of warm, nutrient-rich wastewater effluent are prone to clogging, and that excess carbon and nitrogen exacerbates biological clogging in this setting. In addition, scouring flows and flooding regulate the clogging process. A conceptual model was developed to illustrate some of the factors that affect clogging (Figure 3). In this study, the following questions were addressed:

1. What are the spatial patterns of hydraulic conductivity in the effluent-dominated reaches of the SCR? Are there areas prone to reduced conductivity?

2. Is there temporal variability in hydraulic conductivity associated with flooding? How does sediment microbial abundance respond to flooding?

3. Are there environmental variables, such as nutrients or stream flow, related to differences in hydraulic conductivity and microbial abundance?

Study Area and Experimental Design

Much of the study was conducted as a natural field experiment (sensu Diamond 1986), taking advantage of variability in stream conditions that exist within and between rivers. To address question 1, a gradient of sites were selected near the point of effluent discharge, around 10 km downstream, and near the end of the surface flow. Hydraulic conductivity was measured directly in the streambed to look for trends in reduced conductivity. To address question 2, measurements were made repeatedly over the course of a year to capture flooding and inter-flood periods. To address question 3, physical, chemical, and biological parameters were measured in the surface water and sediments to determine which variables were correlated with reduced conductivity.

The study river (Santa Cruz) and its spatial control (San Pedro) are located within arid to semi-arid basins of southern Arizona (Figure 4). The

Santa Cruz, designated as an effluent-dominated waterway (EDW), receives effluent discharge at two points. Effluent is divided into classes, based on regulations from the Arizona Department of Environmental Quality (Table 1). The first, the Nogales International Wastewater Treatment Plant, was upgraded in the summer of 2009, and is classified as A+ effluent (AZDEQ, 2012). The NIWTP discharges into the Upper Santa Cruz reach near the city of Rio Rico, sustaining nearly 20km of perennial flow. This reach sustains emergent macrophytes on streambanks and dense cottonwood/willow riparian forests on floodplains, and has a shallow groundwater table. The second discharge point, the Ina and Roger Rd Wastewater Treatment Plants, is located in North Tucson. These facilities release B class effluent, lower quality water with high loads of ammonia, into the Lower Santa Cruz reach. Historically, the Lower Santa Cruz was intermittent through this area, but eventually groundwater pumping and channel alteration left the river dewatered. As a result, this reach supports fewer trees, and cottonwoods are especially rare, but the river still maintains thick streamside vegetation. Given the larger Tucson population, three times more effluent is produced and discharged to the river than at the NIWTP and perennial flow is maintained for up to 40km.

A total of nine sites were investigated. Three sites were sampled along the effluent-dominated reach of the Upper Santa Cruz in the Tubac/Nogales area at 3, 11, and 15km downstream of the Nogales International Wastewater Treatment Plant. Three more sites were sampled on the effluent-dominated Lower Santa Cruz (LSC) in the Tucson/Marana area at 0.5, 11, and 25km downstream of the Ina Road treatment facility. The final three were control sites on the San Pedro River (SPR). While the San Pedro River was used as a non-effluent control, it should be noted that the cities of Fort Huachuca, Sierra Vista, and Tombstone utilize recharge facilities that directly inject effluent to the aquifer. Nutrients in the surface water of the San Pedro were barely detectable, however, and so this impact was considered minimal. The San Pedro sites were located at Lewis Springs (31º 33’ 16.81” N 110º 08’ 24.88 W), Charleston Rd (31º 37’ 25.29” N 110º 10’ 16.60 W), and at Fairbank Rd (31º 43’ 7.06” N 110º 11’ 33.12 W).

At each site, three transects were established to span a 200m reach in areas of relatively cobble-free sediments (cobbly areas had to be avoided as they interfere with piezometer installation). At each transect, three locations were randomly selected within a 20m buffer at a bank, a pool, and in the thalweg to cover the range of hydrogeomorphologies in the river. Measurements were taken during April, August, October, and

November of 2010, and May of 2011 to capture seasonal variability. Storm flows occurred between the end of July and the start of August 2010, and the August trip was scheduled during the week following peak flows.

During the summer of 2009, the Nogales WWTP was upgraded, resulting in improved water quality of the discharged effluent. I had visited the sites just prior to the upgrade, but upon returning several months later to collect samples the sites farthest (32km) downstream of the outfall had dried up and appeared to have been dry for weeks or even months. A replacement site was chosen (20km downstream), but then this site experienced drying events. Drying also occurred on the LSC in August after a strong flood, leaving two sites dry (28 and 38km downstream). The loss of sites was unfortunate because it prevented long-term, consistent data collection, making temporal/seasonal comparisons difficult. After August 2009, all of the downstream sites were shifted closer to the treatment plants to avoid continued drying events.

Methods

Saturated hydraulic conductivity

Measuring hydraulic conductivity at single points in a flowing system is not a commonly used methodology. The limited published research on large-scale conductivity measurements in rivers, indicate that hydraulic conductivity is spatially heterogeneous and range by several orders of magnitude (Baxter & Hauer, 2000; Baxter et al., 2003, Calver, 2001). The equipment used in this study was modified several times before an effective design was found. The instruments needed to be capable of measuring a wide range in conductivity at decent resolution, be able to withstand impacts with cobble buried in the sediments, be affordable enough to make multiple pieces, and lightweight enough to carry to pack and carry in the field.

The most successful approach (based on Chen, 2004) was to install temporary in-stream piezometers made of clear pvc, using a falling head test to measure hydraulic conductivity of the sediments. The piezometers were constructed of clear, 4 centimeter (cm) inner diameter pvc pipe cut to 122 centimeter lengths. Piezometers were installed in sets of three at a depth of 10, 15, and 20cm below the sediment surface at each location (thalweg, bank, and pool) allowing a total of 27 piezometers per site. Piezometers were installed manually with a mallet and left to equilibrate for approximately one hour. After this time, the distances from the top of the pipe to the water level inside and outside the pipe were recorded and then clean surface water was slowly added to fill the pipe full. The time it took for the water level in the pipe to fall one cm was recorded and this measurement was repeated two more times for an average. In places of low conductivity, the water level dropped at such a slow rate that the measurement was abbreviated by setting a cut-off time of 10 minutes and the time was recorded as >10 minutes (though it would have been better for data analysis to instead record the distance that the water level had dropped in 10 minutes).

The calculation for saturated hydraulic conductivity (K), based on Chen (2004), was $K = (L/t)\,[\ln(h1/h2)]$

Where:

L = the bottom length of pipe filled with sediments (either 10, 15, or 20cm).

t = the time required for the head to drop 1cm (clogged pipes were stopped at 10min).

h1 = length from the top of the pipe to the surface water level outside the pipe

h2 = h1 – 1cm.

Characterization of sediments and environmental variables

Following conductivity measurements, the 20cm deep pipe was carefully removed from the sediments to provide a sediment core sample. Excess water was poured out of the top of the pipe and the sediments were emptied into a Whirl-pak® bag, transported over ice, and stored at 4ºC until analysis. Notes of visual observations from the core, such as dark iron-reducing layers, gas bubbles, or high organic matter were recorded (Figure 5).

A homogenous subsample of the sediment core was used for biological analysis within a few days of collection. Heterotrophic Plate Counts (HPC) were conducted using Standard Methods (American Public Health Association, 2005). In preparation, wet sediments were packed into 50 milliliter (ml) sterile centrifuge tubes and centrifuged at 5000 rpm for 10 minutes. Excess water was poured off and 50 grams (g) of sediment were transferred into sterile, tarred 500ml plastic bottles. For a 1:10 dilution, 450ml of sterile phosphate buffered solution (PBS) were added to each bottle which was vigorously agitated by hand for five minutes to dislodge attached cells. Promptly after agitation, 100 microliters (µl) of the suspension was transferred aseptically to a set of serial dilution tubes containing 900 µl of sterile PBS. Corresponding duplicate plates of R2A agar received 100 µl from the dilution tubes and were spread dry with sterile glass rods. Inoculated plates were incubated at 35ºC for 72 hours, or until colony numbers were easily countable. Plates containing 30-300 colonies were counted and recorded. Initial wet sediments were weighed, oven dried, and re-weighed to determine the number of colony forming units (CFUs) per gram of dry sediment weight. However, due to some loss of data, results are presented as CFUs per gram of wet sediment weight – the differences between the two measurements were minor (see Appendix A).

The remaining portion of the core sample was oven dried and sieved for texture analysis (modified from Gee & Or, 2002). The sample was sieved into 2 fractions, gravel (> 2 mm) and soil (< 2 mm). A 75g subsample of soil was reserved to determine silt and clay content using the hydrometer method. Following hydrometer measurements, the sample was wet sieved through a 63 µm sieve to retain the sand fraction. The sample was oven dried and then sieved through a stack of sieves to yield very coarse (1000-2000 µm), coarse (500-1000 µm), medium (250-500 µm), fine (125-250 µm), and very fine (63-125 µm) sand fractions.

At each transect, stream discharge was measured using a digital water velocity meter (Global Water). Average velocity was recorded at several vertical points along each transect, and single point readings were taken at each of the piezometer clusters. A surface water sample was collected at the thalweg of each transect and a sediment water sample was collected at each cluster of piezometers. To extract the sediment water, a 1.27cm diameter cpvc pipe with the bottom capped and holes drilled throughout the bottom 38cm was installed next to the piezometers at a depth of 20cm. Vinyl tubing was pushed down to the bottom of the pipe and an Ace brand hand crank pump was attached to the tubing to draw the water up without aerating it. Dissolved oxygen, pH, oxidation-reduction potential (ORP), and temperature were measured in the pumped water using portable multi-parameter meters. Then the water was transferred to acid washed 500 ml plastic bottles. In accordance with EPA regulations (40 Pt. 136.3), samples were transported on ice, stored at 4ºC, and analyzed within 48 hours. Prior to analysis, the bottles were centrifuged at 5000 rpm for 10 minutes to remove particles and then subsamples were pipetted into 3 sets of tubes; ammonia and nitrate/nitrite subsamples were frozen until analysis, non-purgeable organic carbon subsamples were acidified with hydrochloric acid to a pH of 2 and stored at 4ºC until analysis, and total phosphorous subsamples were digested using potassium persulfate and stored at 4ºC until analysis. Analyses were performed by research specialists at the Goldwater Environmental Lab at Arizona State University.

While collecting samples, general observations were recorded, including extent and growth form of algae, macrophytes, types of aquatic organisms, weather, and condition of the channel.

Analysis

Data were visually tested for normality using histograms and normal probability plots. A Shapiro-Wilk test was used for data that were difficult to assess visually. Numerous data sets could not be successfully transformed, so all data were left untransformed and analyzed with non-parametric Spearman's rank-order correlation. Spearman's correlations were used to examine the strength of relationships between hydraulic conductivity, bacterial counts, and environmental variables. Cases with n < 6 were excluded from the results. Many of the variables were highly autocorrelated, so multiple regression was not utilized. Data were analyzed with SPSS software.

Results

Are there spatial patterns of hydraulic conductivity associated with effluent?

During the course of this study, average saturated hydraulic conductivity on the A+ class SCR as a whole was 1.4-3.1 times higher than the B class SCR (Figure 6). Readings ranged from 3.0×10^{-4} to 4.0×10^{-1} cm s^{-1} on the B class reach, and from 4.0×10^{-4} to 7.8×10^{-1} cm s^{-1} on the A+ class reach. On both of the effluent-dominated reaches, conductivity increased with distance from the effluent outfall: the A+ class by an average of 29% and the B class by an impressive 58%. This was most clearly seen in the banks and pools. Thalwegs usually contained unconsolidated, sandy sediments and maintained consistently higher conductivity readings.

Conductivity rates on the San Pedro control sites were lower than expected (Figure 6: L, C, F). Measurements ranged from 3.0×10^{-4} to 1.7×10^{-1} cm s^{-1}, with one outlier reading at 3.1×10^{-1} cm s^{-1}. This range was markedly below the B class SCR. It was concluded that the control sites were not good hydrogeomorphic comparisons to the SCR, but SPR conductivity was sampled once more at the end of the study (5/2011). At this time Charleston, a wide, shallow sandy site was added to the SPR sites, and was clearly a better hydrogeomorphic comparison with the SCR. Charleston conductivity readings were similar to the SCR A+ class site at 3km.

Physical and biological clogging is most likely to occur in the top few centimeters of sediments. However, this study did not find clear patterns in conductivity by depth (10, 10-15, and 15-20cm) (Appendix B). Locations could be considered to be clogged when rates fell below 5.0 x 10-2 cm s^{-1}. This would include all of the 0.5km B class locations during May, as well as most of the banks and pools sampled at other sites that month.

Is there temporal variability in hydraulic conductivity and microbial abundance in response to flooding?

Flooding had a pronounced effect on conductivity rates. In August, summer rains produced a 16,800 cfs (476 cms) flood on the B class reach, and a 5,510 cfs (156 cms) flood on the A+ reach (Figures 7, 8). Measurements were made within 5 days of the flooding during 8/2010. While average conductivity readings did not increase greatly at most sites, bank and pool measurements went from near-zero to matching thalweg measurements (Figure 6). Other effects were more noticeable; floods in the magnitude of 16,800 cfs only occur a couple times per decade on the LSC, and following this event, the 28km site had dried temporarily.

Upon sampling two months later in October, the effects of flooding on conductivity were diminishing. Pools were beginning to clog, but many of the readings still exceeded 0.2 cm s^{-1}(Figure 6). By the last sampling period in May, flooding had not occurred at the sites for 7 months. Conductivity correspondingly decreased over this time period on the effluent-dominated sites. At this stage there were few measurements above 0.2 cm s^{-1}. Even thalweg readings were decreasing.

On the SPR, a smaller flood, 1,060 cfs had occurred the day before the 8/2010 sampling (Figure 9). Surface waters were brown with suspended sediments and flows were still strong enough at that data could not be collected at all locations. With only two months of data to compare, trends can be difficult to see, but conductivity appears to have increased slightly despite the lack of flooding between 10/2010 and 5/2011 (Figure 6, C, L, F).

Microbial sampling began in August during flooding, so there was no pre-disturbance baseline to start with. Flooding on the A+ reach peaked at 156 cm s^{-1}, but the B class reach flood was three times stronger at 476 cm s^{-1}. Microbial counts of B class thalwegs and pools were lower than the A+ at this time, but were also the lowest of all the sampling periods for that site (Figure 10). Once the flooding disturbance had passed, the B class reach usually maintained higher counts than the A+ sites.

The highest counts during the August flood occurred on the SPR at 2.0 x 10^9 CFUs per gram of wet sediment. The SPR counts may have been higher than the other sites because the surrounding area is wilderness and runoff would have introduced large quantities of microorganisms. By October, the high microbial numbers had dropped to a level that was maintained for the rest of the study period.

Are there environmental variables, such as nutrients or stream flow, related to differences in hydraulic conductivity and microbial abundance?

Microbial abundance. Post-flooding, the B class counts were higher than the A+, ranging $1.3 \times 10^7 – 3.6 \times 10^9$ vs. 3.0×10^7 to 7.9×10^9 CFUs. SPR counts ranged from 5.3×10^7 to 2.0×10^9. Counts from pools ranged higher than the thalwegs, often by an order of magnitude or more. However, river sediments are heterogeneous, and at times the differences were minimal or thalwegs produced higher counts.

Plate counts from the B class reach were highest near the effluent outfall, and decreased with distance downstream (Figure 10). This trend was not as clearly observed on the A+ reach. Pool numbers were higher than thalwegs as well. Between October and May, B class pool counts were 20 times higher (8 times if the November 25km site is removed), A+ counts were 10 times higher, and SPR counts were only 4.5 times higher.

During most of the study, one thalweg and one pool were randomly selected for counts at each site, but during November, the B class 0.5km site had three pools selected to examine the variation that might occur over a 200 m wide sample area. Counts from the three pools were 6.2×10^8, 1.6×10^9, and 2.0×10^7, a threefold difference.

In November a bank sediment core was selected from the 25km B class site for signs of biological activity (black sediments at the bottom). The top of the core was sampled from the clean, coarse sand, and then the thick black sediments were sampled from the bottom. The top of the core yielded a count of 6.3×10^7 while the count from the bottom was 3.0×10^8 CFUs. Colonies that grew on the bottom plate appeared to be dominated by one type of organism, and a strong earthy smell suggested Actinobacteria.

Sediment texture. Most of the SCR streambed was composed of coarse to very coarse sand (Appendix D). Fine sands, silt, and clay, lumped together as fine sediments at 0.125 mm and smaller, pack tightly and restrict the flow of water, so they were focused on for reductions in conductivity. Fines were highly negatively correlated with conductivity throughout the study (Table 1); the strongest relationships were found on the B class reach. Fines generally decreased with distance downstream from the effluent discharge (Figure 11). They also concentrated more along the slower-flowing banks and pools, especially on the B class reach. The composition of fines on the B class sites ranged from 0.8-70%, while the A+ class sites ranged 2-25%. The SPR contained a midrange of 6-53% fines. The B class 38km site was abandoned after April, due to its dissimilarity to the other SCR sites; samples along the banks contained up to 98% fines, perhaps a result of being surrounded by open desert and agricultural land.

August flooding most notably flushed out the pools, leaving lower concentrations of fines. On the A+ reach, it took 9 months for the river to re-accumulate these fines. The opposite trend was observed on the SPR, where flooding introduced large quantities of fines that eventually washed out over the following months.

Water quality. The San Pedro control sites maintained near-zero nutrient levels in surface waters in contrast with the higher nutrient levels contributed by effluent in the Santa Cruz. The improvements in wastewater treatment technology were clearly identifiable between the two reaches of the SCR, where the A+ USC surface water quality surpassed the LSC water quality for most variables measured. Ammonia stayed below 1 mg L^{-1} in the A+ SCR effluent, while the B class waters averaged 15 mg L^{-1} (Figure 12). High ammonia concentrations did decrease with distance downstream, but after 25-38 km, levels still hovered around 10mg L^{-1}. Similar concentrations of ammonia were found in the river sediments, though less so in the slower flowing banks and pools. SPR sites occasionally had higher concentrations of ammonia in the sediments as well, though rarely over 1 mg L^{-1}.

On the effluent-dominated sites, nitrates fell into two patterns: either decreasing with distance downstream, or increasing (Figure 13). On the A+ reach nitrates decreased. Initial concentrations of nitrate at the 3km ranged from 2-8 mg L^{-1} through the year, where higher concentrations occurred from August through November, coupled with higher removal rates. Since 2mg L^{-1} NO3 were still present at the 20km site, nitrates, like ammonia, are probably not completely removed from the surface water before the river stops flowing. These concentrations are still eutrophic compared to the SPR.

Surprisingly, the B class effluent introduced less nitrates to the river than the A+ effluent. However, on the B class reach, nitrates increased 2-3 fold between the first and last site (Figure 13). Nitrate inputs did not fluctuate with the B class as they did with the A+ class effluent. Sediment concentrations occasionally spiked above surface water levels, but generally nitrates were being removed in the slower flowing banks and pools.

Total phosphorous (TP) levels were near zero in SPR surface waters, except during flooding, but the SCR maintained steady concentrations of 2-4 mg L^{-1} (Figure 14). When not disturbed by flooding, sediment TP concentrations equalized with surface water concentrations on the effluent dominated sites. Flood events appeared to cause large spikes of TP in sediment water, but not surface water (Figure 14, 8/2012), and the residual effects were still present 2 months later. TP concentrations in the surface water did not strongly decrease with distance downstream of the effluent outfall.

Organic carbon (NPOC) concentrations in the SPR varied by 10mg L^{-1} over the span of a year (Figure 15). Spikes in carbon coincided with floods and the fall season, but in between these events carbon levels were in the 1-2mg L^{-1} range. On the effluent-dominated sites, the B class reach contained carbon in the 9-13 mg L^{-1} range, while the A+ class spanned 2-9 mg L^{-1}. Carbon concentrations decreased with distance downstream, but the rate of decline slowed during flooding and cooler temperatures in November.

The percentage of nutrient removal on the EDWs (calculated as the difference between surface concentrations at the first and last sites) was higher on the A+ class reach (Figure 16). This result is counterintuitive given the higher temperatures year-round (Figure 17), and the greater availability of nutrients on the B class reach. Temperature did seem to be an important factor, as removal rates declined during cooler winter temperatures (11/2010). Besides nitrates, which were generated within the B class reach, the two reaches followed similar patterns of removal through the study period.

The temperature of the effluent leaving the B class treatment facility was 5-15 °C warmer than the SPR, while the A+ class water was 2-12 °C warmer (Figure 17). After flowing 15km downstream, the A+ class water temperature was similar to the SPR. The B class site at 0.5 km maintained temperatures above 25°C throughout the year, and the temperature effect of the effluent persisted to the downstream sites.

B class effluent contained slightly lower concentrations (~6 mg L^{-1}) of dissolved oxygen than the A+ (7-9 mg L^{-1}) (Figure 18), and this was after strong churning action from being discharged into the river from an elevated pipe and then cascading over a check dam. The SPR maintained DO in the more desirable range of 8-13 mg L^{-1}. In part, microbial respiration depleted oxygen in the sediments, but there were not consistent downstream or seasonal patterns in DO.

Local soils are alkaline, so water bodies tend to have a pH around 8, as was the case for the SPR (Figure 19). The pH of the effluent-dominated reaches was usually slightly lower, in the 7 range. The pH of sediments will drop in response to microbial metabolism releasing carbon dioxide. During the warmer month of May, sediment pH measurements were at their lowest. August is also a warm month, but the flood appears to have disrupted microbial respiration at most sites, leaving the pH at surface water levels. Data points are missing because measurements were difficult make in effluent. The water chemistry affected the electrodes enough that the pH meter would stop working.

Oxidation reduction potential (ORP) was used to measure if water conditions were in a state of receiving or donating electrons, an indication of which microbial metabolisms would be active. At all of the sites during this study, ORP levels exceeded 300mv only three times, all of which occurred during October (Figure 20). The lowest ORP values overlapped areas of low conductivity on the B class reach and the SPR. Flooding in August raised the B class ORP to A+ levels, but one month later it had returned to pre-flood levels. Negative values were never measured on the A+ class reach.

Stream discharge represents the time period that samples were collected, and does not account for the daily fluctuations of effluent released from the WWTP. SPR flows fell under 0.5 $m^3 s^{-1}$, while the SCR maintained 0.5-2 $m^3 s^{-1}$(Figure 21). Pool locations often had near zero flows, while thalwegs were the fastest moving part of the channel. During April, the 0.5km B class site had strong flows, but in August the channel shifted after flooding and the change in bed conformation slowed stream flows. Rainfall had not occurred during November, but flows on the B class were notably higher. This is likely due to increased discharge from the WWTP.

Field observations. Visual observations made while collecting samples contributed additional information. The most striking event was site drying. In June of 2009, the Nogales WWTP upgrades resulted in improved water quality. A site being monitored at 32km downstream of the outfall was flowing in May 2009, but by December of 2009 it was completely dry. This implicates water quality as a strong factor driving clogging in the Santa Cruz. Two sites also temporarily dried on the B class reach after the 16,800 cfs flood in August 2010.

Visual indications of microbial activity were frequent at sites that had stagnant flow and lower conductivity measurements. Sediment cores from such sites had dark layers of iron sulfide that occur in strongly reducing, anaerobic zones (Figure 5). These sediments and their porewater smelled strongly of sulfur. Some samples contained clumps of organic matter that caused the sediments to clump together, and oftentimes porewater could not be extracted. A few cores contained large gas bubbles from microbial metabolism that became trapped in the sediments (Figure 5). The B class reach, especially the 0.5 km site, was notorious for these types of sediments that appeared to be microbial hotspots of activity. On two occasions, large areas of the streambed had become saturated with gases and the pressure of walking through the river would cause streams of bubbles to pour out of exit points like geysers. Aside from the occasional pocket of clayey, black sediments, such unusual observations were never noted on the SPR.

Discussion

Are there spatial patterns of hydraulic conductivity associated with effluent?

This study demonstrates that there are spatial patterns of hydraulic conductivity associated with effluent. Distinct differences were found between low, moderate, and highly impacted streams receiving treated wastewater. Wide-scale measurements of saturated hydraulic conductivity revealed that the highly-impacted B class reach maintained lower measurements (7.6×10^{-2} average) than the A+ class reach (1.4×10^{-1} average). In addition, conductivity rates increased with distance downstream from the effluent discharge for both reaches, by as much as 58% on the B class reach and 29% on the A+ class reach. Areas most prone to reduced conductivity rates were located at the edges of the river at bank and pool sites.

Conductivity readings from this study varied widely from other infiltration studies conducted on the Santa Cruz River. On the B class reach:

- Matlock (1966) found an average of 7.1×10^{-4} cm s^{-1}
- Sebenik (1975) found an average of 3.5×10^{-4}
- Lacher (1996) determined a range of 3.0×10^{-4} – 1.1×10^{-3}
- Canfield et al. (2010), using Lacher's model, found K had declined to 2.5×10^{-4}
- This study measured a range of 3.0×10^{-4} – 4.0×10^{-1}, averaging 7.6×10^{-2}

On the A+ class reach:

- Treese et al. (2009) reported averages for three stages: 4.3×10^{-1}, clogged at 1.6×10^{-1}, then post-flood at 2.9×10^{-1}
- This study measured a range of 4.0×10^{-4} to 7.8×10^{-1}, averaging 1.4×10^{-1} (or, averaging 1.0×10^{-1} clogged, and 2.0×10^{-1} post flood)

Conductivity rates on the B class reach were 2 orders of magnitude greater than other studies conducted over the last four decades. The most likely reason that conductivity was higher for this study is a result of how the measurements were made; conductivity was calculated from direct in-stream measurements spanning 200m wide sites. Most studies have not utilized direct in-stream measurements, but instead, calculate conductivity using numerical models, aquifer pumping tests, grain size analysis, or tracer studies (Landon et al., 2001). Calver (2001) concluded that conductivity determined at larger scales by numerical modeling tends yields conservative results compared to field and laboratory methods. While Cardenas & Zlotnik (2003) noted that studies utilizing direct measurements flowing water bodies are rare, Landon et al. (2001) found that slug tests with manually driven piezometers were the most accurate method for determining conductivity of sandy streambeds.

Treese and others (2009) collected sediment cores from the riverbed of the A+ reach, and then measured conductivity of the cores in the lab. This method was similar to direct measurements in the riverbed and the results were within the range of this study. Direct hydrologic measurements taken from other rivers also approximate this study. Chen (2004), the source of the method used in this study, reported conductivities of $1.7 \times 10^{-2} - 5.4 \times 10^{-2}$ for sandy locations and 1.9×10^{-3} for silt-clay locations in sandy rivers in Nebraska. Given the shortage of comparable methods in effluent-dominated waterways, results from this study appear to fall within an expected range for the method used.

Houston and others (1999) defined a clogging layer (in infiltration basins) as a zone where a sharp drop in hydraulic head occurs. However, clogging does not seem to have a defined numerical value. Clogging has an inherent temporal factor, so determining when a material is clogged takes multiple observations over time. For this study, thalweg measurements were considered to be, for the most part, the optimal high conductivity for a reach under current conditions. In contrast, clogged conditions were considered to have developed when falling head tests required several minutes to conduct (usually banks and pools, in the absence of flooding).

Is there temporal variability in hydraulic conductivity and microbial abundance in response to flooding?

Conductivity rates, percent fines, and microbial abundance were all altered by flood pulses. For conductivity, flooding had the largest impact on banks and pools, increasing rates to levels normally seen in the thalwegs. The flooding that occurred on the B class reach during this study restored conductivity to the point that the river dried temporarily at 28km downstream. On the SCR, conductivity gradually declined over a period of nine months without flooding. Presumably, in the absence of flooding, conductivity rates would continue to decline to the point where water percolating from the active channel would be severely restricted, potentially affecting riparian trees during drought (Treese et al., 2009), and extending the distance that the river flows downstream.

The effect of flooding on percent fines was similar to conductivity; pools were scoured and eroded of fines, and over the following months, fines re-accumulated in the pools. The similar pattern between conductivity and fines indicates a strong link. Flooding resulted in decreased microbial abundance, and it appeared that stronger flows caused larger reductions in biomass. However, biomass was quick to recover. Two months after strong flooding on the B class reach, pool microbes had recovered and increased by 12 times. These results show that microbial abundance can recover quickly after disturbance, yet conductivity and fines return to pre-flood states at a more gradual rate.

Microbial counts reflected the heterogeneous nature of a riverbed, and the variable counts may have decreased the correlation results. A larger sample size may have produced more consistent results, especially since some data were removed from the analyses due to low n, but time and labor for plate counts had to be balanced with the other analyses.

Daily fluctuations in stream flow between the two reaches did not have the expected outcome. The WWTPs discharge water in predictable pulses, as urban water use rises and falls during the day and season. The B class reach discharges more water than the A+ reach, averaging a range of 10-110 cfs vs. 0.5-30 cfs, respectively. Regardless of the stronger flows, the B class reach maintained lower conductivity. Marsh (1968) conducted flume studies using Santa Cruz River sediments, and determined that stream flow eroded the bed and improved infiltration, but the concentration of suspended sediments was a more important factor in regulating conductivity. Another flume study by Ryder and others (2006) found that filamentous green algae were completely scoured off of the sediments at velocities of 0.55 m s-1. Point measurements on the Santa Cruz often reached this range, and may explain why extensive photosynthetic biofilms were not commonly encountered during this study, and thus may not have contributed to the clogging process.

Are there environmental variables, such as nutrients or stream flow, related to differences in hydraulic conductivity and microbial abundance?

While there were distinct patterns between the B class and A+ class reach, the difficulty lies in determining what causes the lower conductivity of the B class reach. This study may not have sufficient data to answer that question. The major differences between the two reaches were: on the B class reach, pools and banks tended to accumulate more fines, annual discharge was stronger (by 3.75 times), ammonia concentrations were 10-20 mg/L greater, nitrates were generated, and ORP was lower with frequent negative values.

The variable with the strongest consistent correlation to conductivity was percent fines. With distance downstream, conductivity rates increased and percent fines generally decreased. The relationship between fine sediments and reduced conductivity has been demonstrated in the literature (Schälchli, 1992; Brunke, 1999). These studies examined how suspended fine particles (clay, silt, and organics) are strained out in the riverbed, causing surface sediments to clog. Fine textured sediments are more prone to trap suspended sediments and clog (Sepaskhah & Sokoot, 2010), as are stable sediments (Packman & MacKay, 2003). Experiments conducted by Packman and MacKay required only small accumulations of suspended clay to cause clogging.

Research on riverbed clogging often includes suspended solids or fines as an important variable for clogging. Suspended solids were not sampled in this study, but it is likely that they exist in higher concentrations on the B class reach, and would have decreased with distance downstream. The Nogales WWTP upgrade in 2009 reduced the amount of suspended solids discharged from around 30mg/L to the current 1 mg/L (Vandervoet, 2009), but a similar upgrade for the B class reach will not be completed until 2013. Currently, the Tucson WWTP stays below the permitted limit for suspended solids (45mg/L). The pending upgrade should result in conductivity rates similar to the A+ reach.

Conductivity and microbial counts were also negatively correlated, but this relationship was confounded by the positive correlation between microbes and fines. Fine sediments offer higher surface area per volume for bacteria to colonize; in addition, fines trap organic carbon and nitrogen that microbes require for growth (Garcia-Ruiz et al., 1998). While Santmire and Leff (2007a) found that sediment size influenced bacterial abundance (abundance was greater on 5mm diameter beads than 0.1mm), but surface area alone did not explain the differences. They proposed that sediment size influences conductivity and porewater chemistry, which in turn, drives the microbial community. Fines, conductivity, and microbial counts are clearly interrelated, and require controlled laboratory manipulations to examine whether conductivity is being driven more by biotic or abiotic processes. Due to funding and time limitations, laboratory column experiments were not conducted during this study.

As early as 1966, Matlock had reported that nitrates increased downstream of the WWTP on the B class reach, a trend that was still apparent during this study. Ammonia concentrations of up to 21 mg L^{-1} were detected at the 0.5 km site. Ammonia serves as an energy source for nitrifying bacteria, and is transformed through a multi-step process to nitrate. The nitrification process occurs predominantly in the sediments and is not limited by organic carbon, as the bacteria are autotrophic and utilize carbon dioxide. Less than 1 mg L^{-1} ammonia enters the A+ class reach via effluent.

The A+ effluent presented higher water quality in all the variables measured except for nitrate. Nitrates persisted to the downstream sites on both reaches, and while concentrations remained below the 10 mg L^{-1} regulated for human health, these concentrations can contribute to eutrophic conditions for the ecosystem. Nitrogen was the nutrient that varied most between the two SCR reaches, and may be in part responsible for the higher microbial counts on the B class reach. Further work would be needed to support this hypothesis, and recent developments in quantitative molecular techniques would help in investigating further.

The plating method used to count microorganisms in this study excluded strictly anaerobic organisms. In samples where fines were high and conductivity was low, these organisms might have been dominant, but were not included in the data. Given the negative ORP conditions in the B class sediments, and regular olfactory detection of sulfur byproducts, anaerobic processes are likely more common on the B class reach. Cultural methods were able to detect difference in microbial abundance between the reaches, but again, quantitative molecular techniques would fill in additional details about which organisms may be dominant on each reach.

Given the detailed information that molecular methods provide, cultural methods like plate counts are being phased out. Comparable studies of heterotrophic counts in effluent were not available. However, Wakelin and others (2008), used chloroform fumigation to study an Australian creek receiving WWTP effluent. They found that microbial abundance increased by 2-fold at 1 km downstream of the outfall, but the lowest abundance was found at the outfall point. Yet, they found that diversity was highest at the outfall point. Ruggiero and others (2006), studied an Italian river that receives effluent from two WWTPs, detecting a 7-fold increase in microbial activity than what occurred at the pre-effluent upstream reach.
This study found the highest microbial abundances to be at the sites closest to the outfall, which decreased with distance downstream. Counts from the control sites were comparable to the downstream sites of the B class reach. Microbial abundance in this study was similar to counts found in other rivers (see Amalfitano et al., 2008; Fischer et al., 2002; Rubin & Leff, 2007)

Denitrification, the transformation of nitrate to nitrogen gas, was once thought to be a strictly anaerobic process carried out by facultative anaerobes when oxygen was depleted. It has since been determined that denitrification can occur under aerobic conditions, and that wide arrays of ubiquitous microorganisms are capable of aerobic denitrification (Lloyd, 1993). As a result, denitrifiers are probably represented in the microbial counts for this study. Denitrification is clearly occurring on the A+ reach, but the trend is masked by nitrification on the B reach. The rate of nitrate removal may be dependent on nitrate surface water concentrations, or may be slowed under lower conductivity conditions; however, it is difficult to tell which factor is more important.

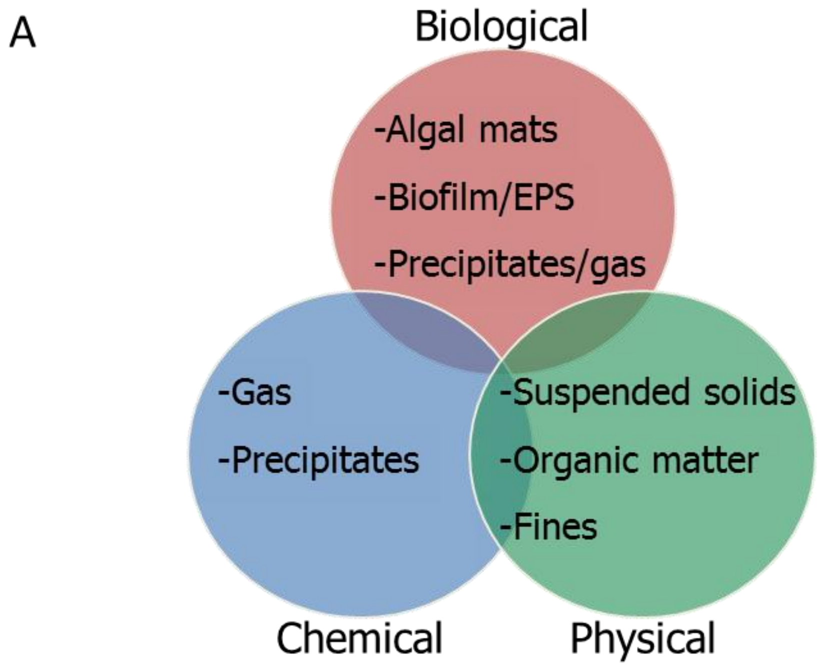
Esposito (1993) described a phenomenon on the B class reach where a perched water table developed above a layer of black sediments in the B class reach. Esposito also reports that methanol delivered in the effluent can serve as a carbon source for denitrification. Under these conditions, the riverbed would act as a “denitrification reactor”. It should be emphasized that while the black layer may be referred to as the clogging layer, there is little research to support the idea that it causes clogging (Baveye et al., 1998). Most likely, the black layer develops under clogged conditions (Herbert, 1976), including low conductivity, low ORP, and anaerobic microbial by-products that precipitate as FeS.

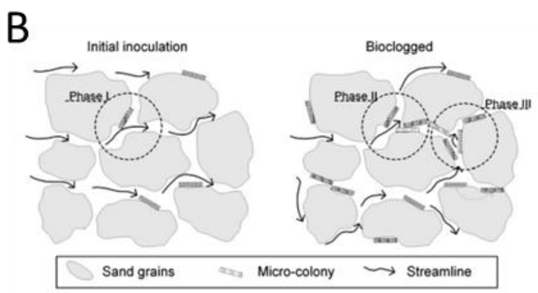
Conclusions

The recent history of the Santa Cruz River is riddled with human alterations. Today, effluent provides the only means for sustained surface water flows in the river. Comparing the two reaches of the river reveals that the quality of the effluent has large-scale impacts, from the types of aquatic organisms able to live in the river, to the condition of the hyporheic zone, the extent of aquifer recharge, and out to the surrounding riparian community. The A+ reach in Noglaes demonstrates that using lower nutrient water with minimal suspended fines can sustain hydraulic conductivity rates comparable to rivers not fed by effluent. Less desirable qualities, like large patches of anaerobic sediments and low diversity of instream fauna, can also be avoided by using higher quality effluent and maintaining moderate streamflows.

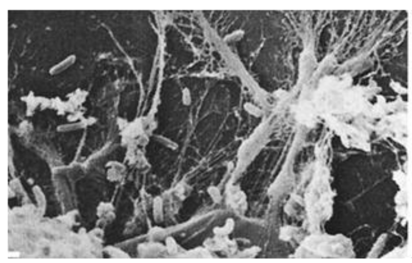
While additional studies under controlled conditions will be needed to determine the specific cause of lower conductivity in the B class reach, river managers and operators of municipal wastewater treatment plants can use the results from this study to inform their actions.

Figure 1 Aerial photo of the Upper Santa Cruz River near Rio Rico showing riparian forest die-off during the spring of 2005. Affected species include cottonwood, willow, hackberry, seepwillow, and mesquite. Photo provided by the Friends of the Santa Cruz River.





From Seifert & Engesgaard, 2007



SEM of bacteria attached to sand grains. From Mattison et al., 2002

Figure 2 **A**. Detail of clogging illustrating the interrelatedness of biological, physical, and chemical effects. **B**. Clogging at the level of sand grains fills up interstitial spaces that water flows through. Bacteria can form large, sticky networks of exopolysaccharides that bridge interstitial spaces.

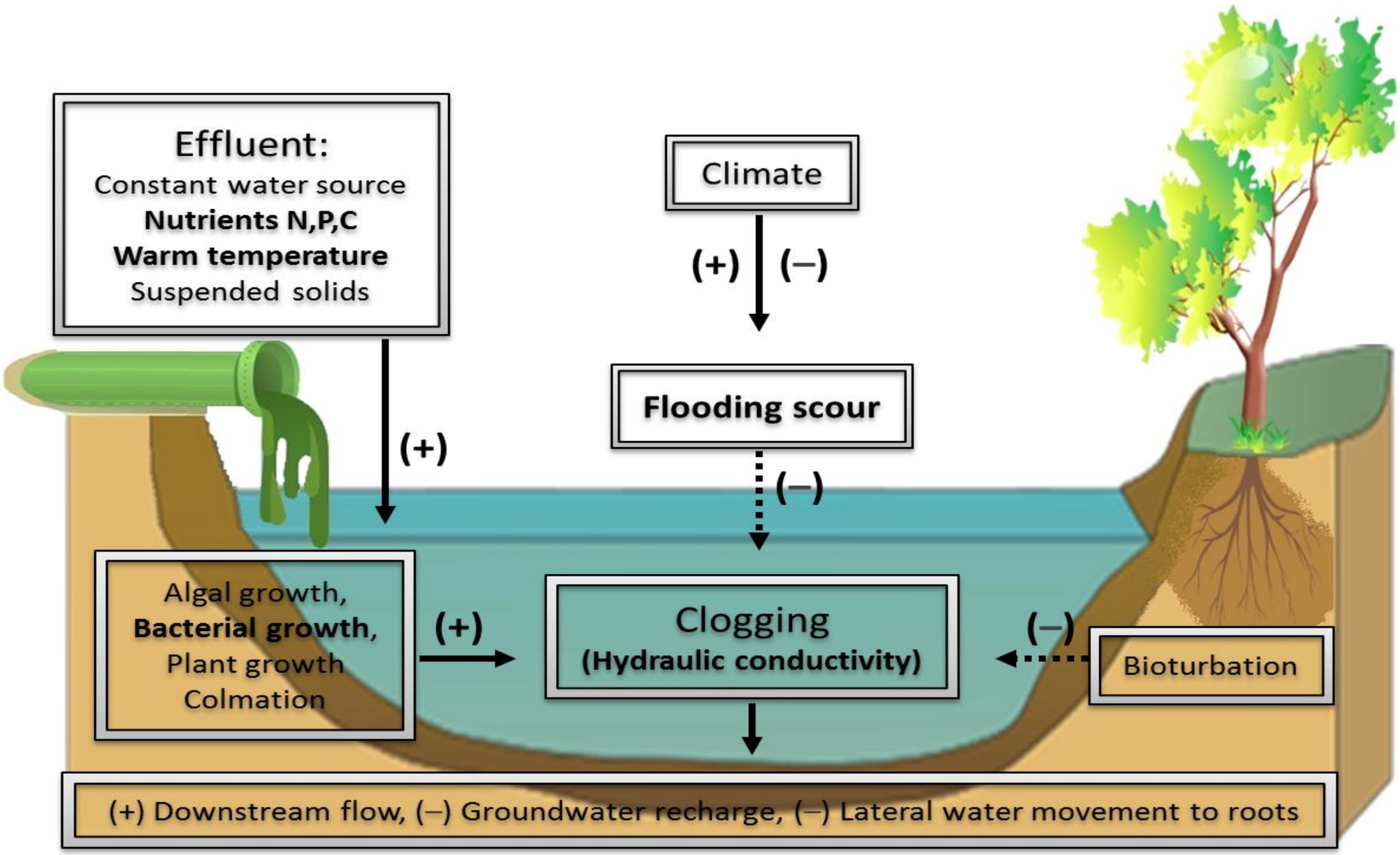


Figure 3 Conceptual model of clogging in an effluent-dominated waterway. Some variables promote clogging (+), while others reduce clogging (-). Variables in bold were measured in this study.

Figure 4 Study area showing nine sample sites. On the Santa Cruz River, three were located downstream of the B class Tucson treatment facility, and three were downstream of the A+ class Nogales treatment facility. Three control sites were spaced along the San Pedro River.

Table 1 Arizona Department of Environmental Quality Reclaimed Water Permit for Reuse of Reclaimed Water

	Class A^+: R18-11-303	Class B: R18-11-306
Applications	Risk of human exposure to potential pathogens in the reclaimed water is relatively high	Risk of human exposure is lower
Treatment	Secondary treatment, filtration, nitrogen removal treatment, and disinfection	Secondary treatment and disinfection
Turbidity limits	≤ 5 NTUs	
Fecal Coliform Colony Forming Units (CFU) limits	< 23 / 100 ml	< 800 / 100 ml
TN limits	< 10 mg/L	

Figure 5 Examples of sediment cores collected on the Santa Cruz River range from coarse unconsolidated sand (left), to tightly-packed fine sediments (middle), and sediments with clear signs of biological activity like black FeS deposits and buildup of metabolic gases (right).

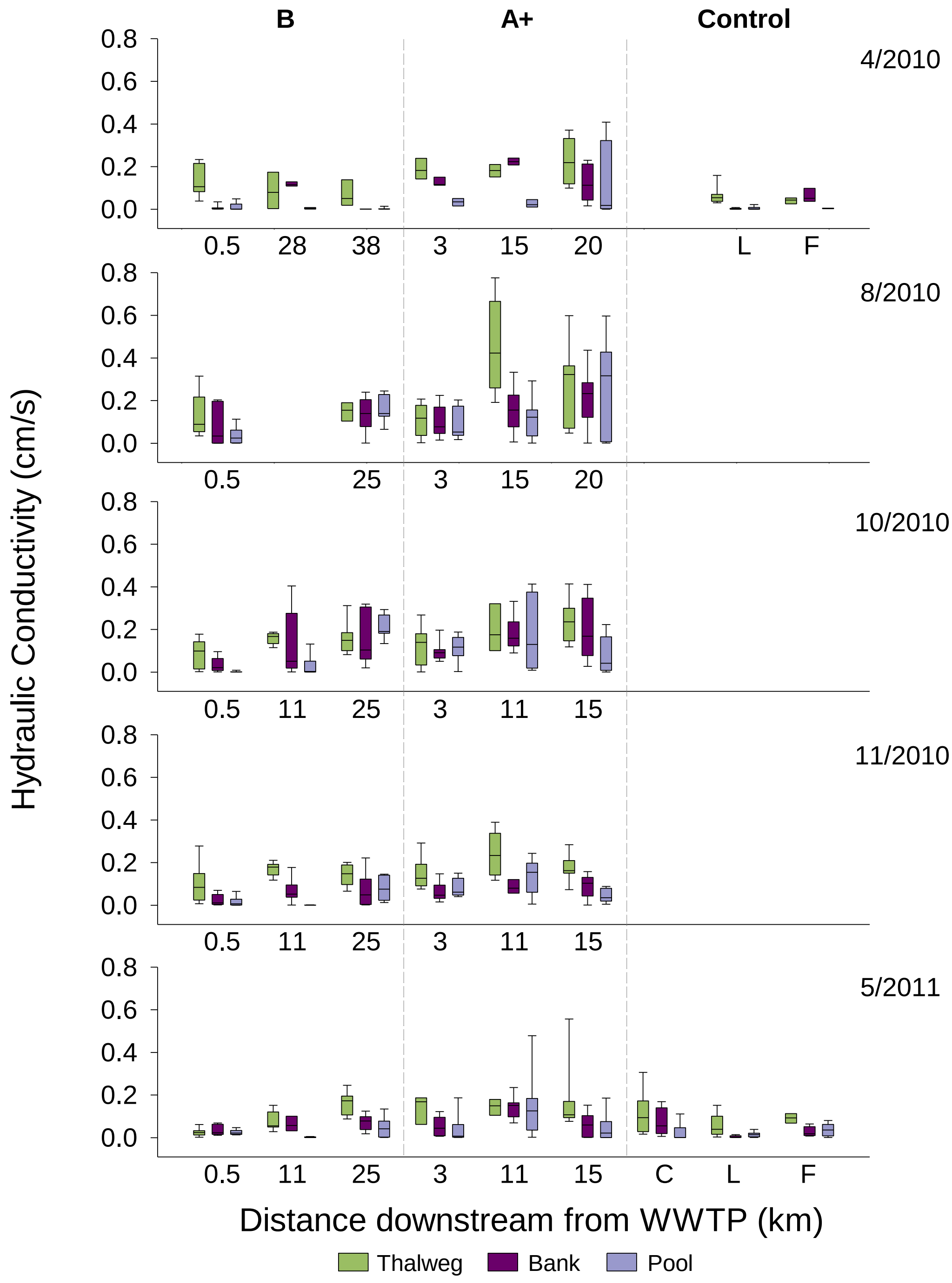


Figure 6 Average saturated hydraulic conductivity of sediments measured with falling head tests in piezometers at 10-20cm deep, spanning 200m. Data were collected over 13 months at the B class Lower Santa Cruz, and A+ Upper Santa Cruz at increasing distance from effluent discharge. Non-effluent control sites on the San Pedro included Lewis Springs (L), Charleston (C), and Fairbank (F) were also measured.

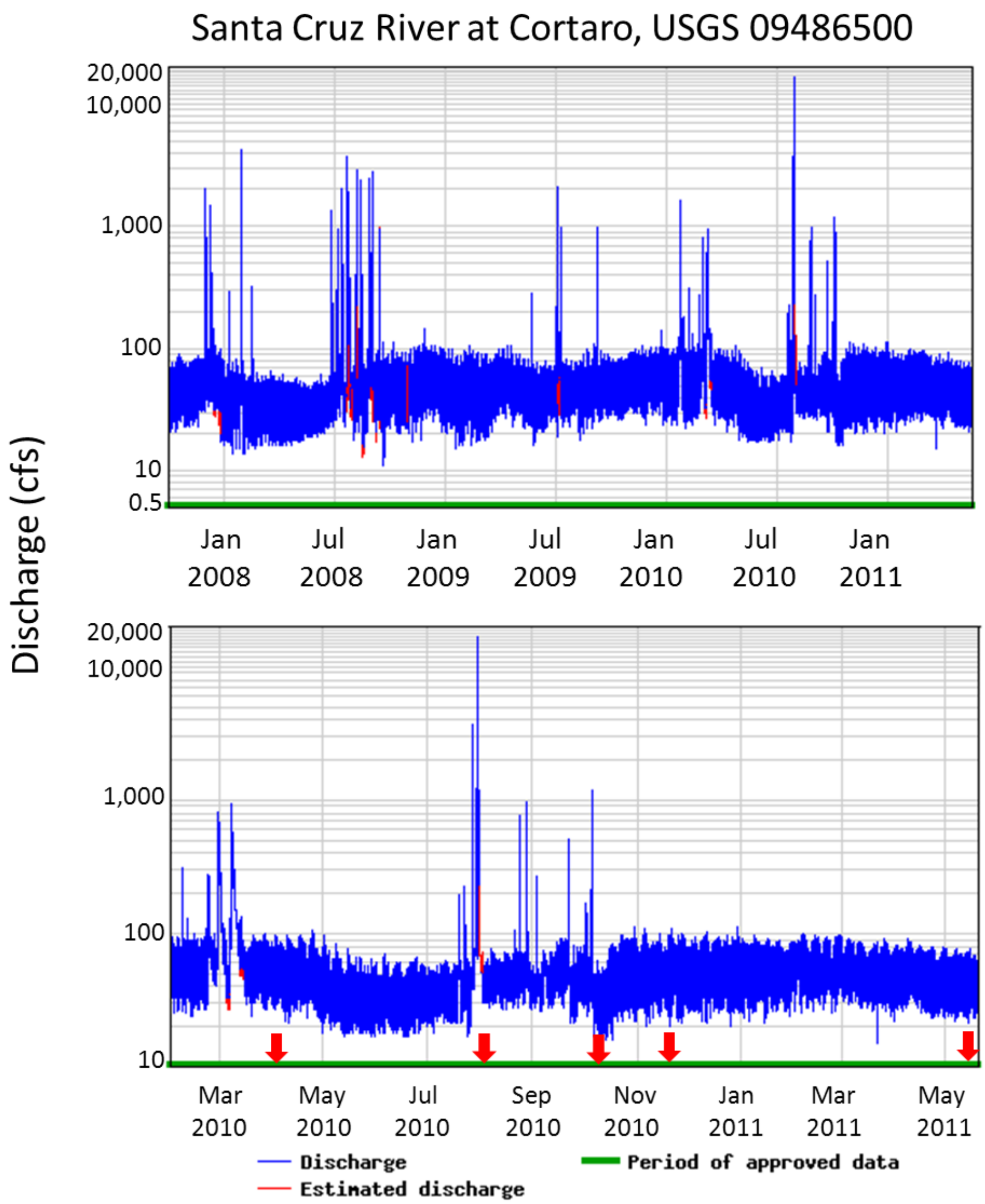


Figure 7 Flood events on the Lower Santa Cruz River (B class) over the last 5 years (top) and during the study period (bottom). Red arrows indicate sampling times.

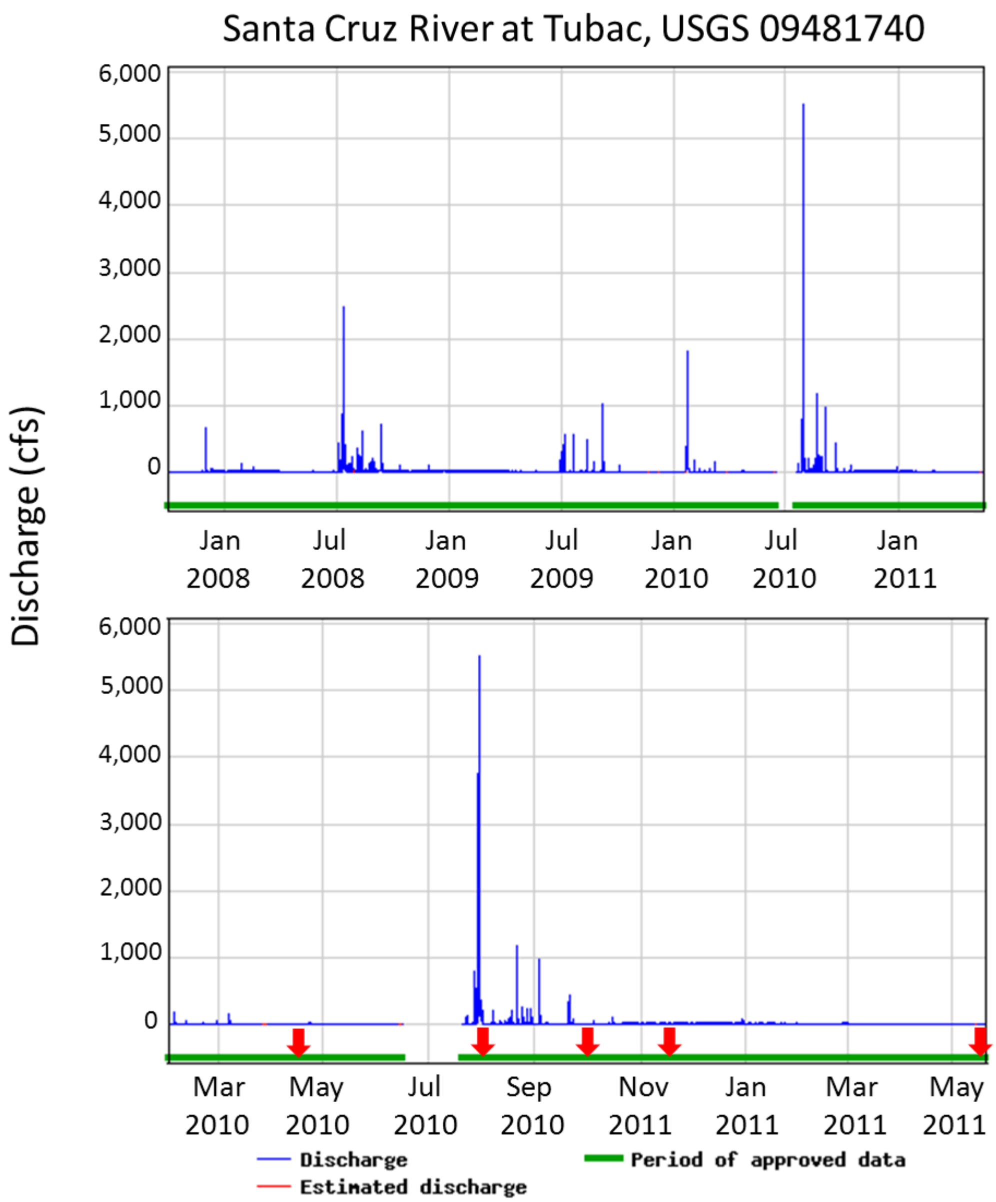


Figure 8 Flood events on the Upper Santa Cruz River (A+ class) over the last 5 years (top) and during the study period (bottom). Red arrows indicate sampling times.

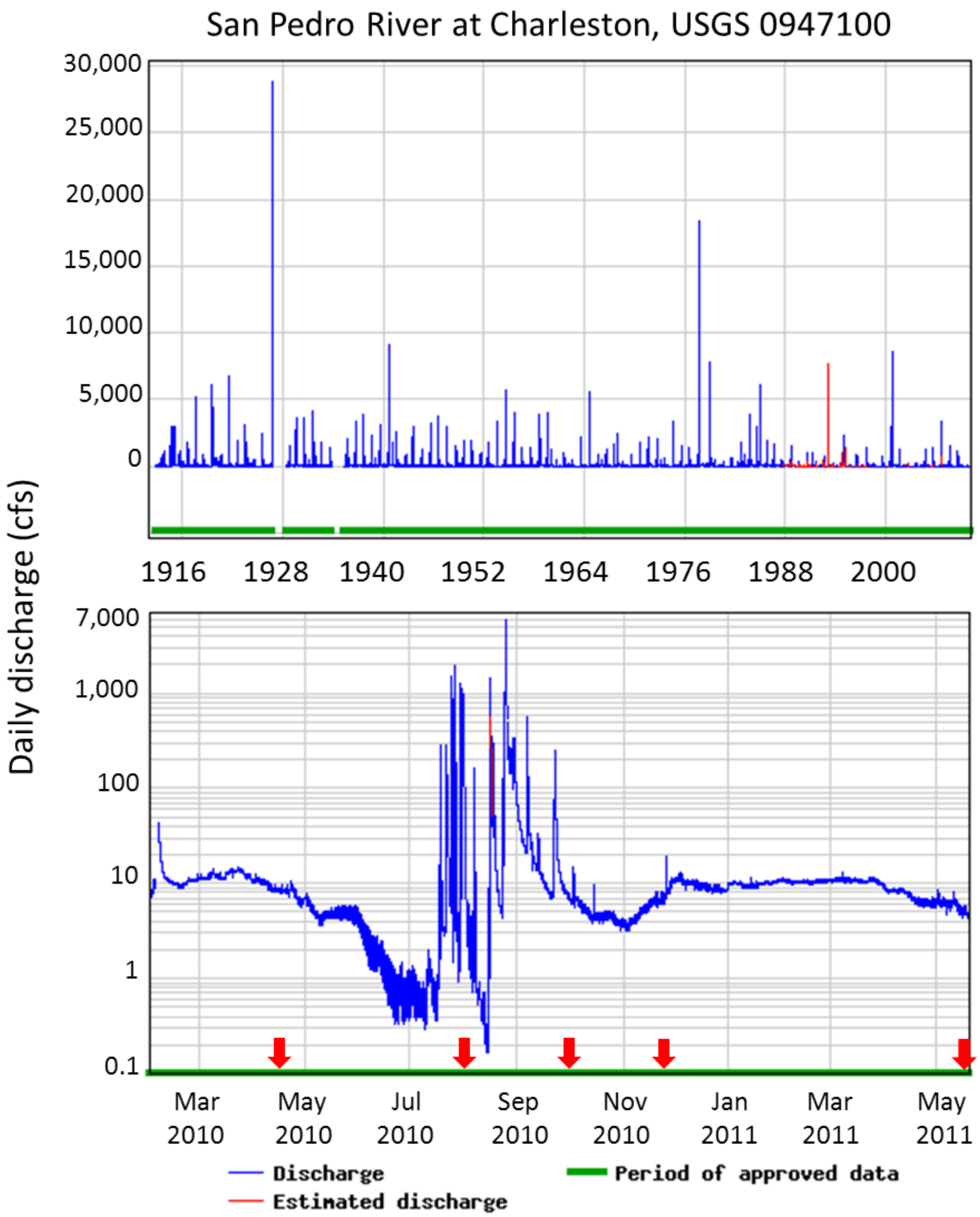


Figure 9 Flood events on the San Pedro River (control) over the last 96 years (top) and during the study period (bottom). Red arrows indicate sampling times.

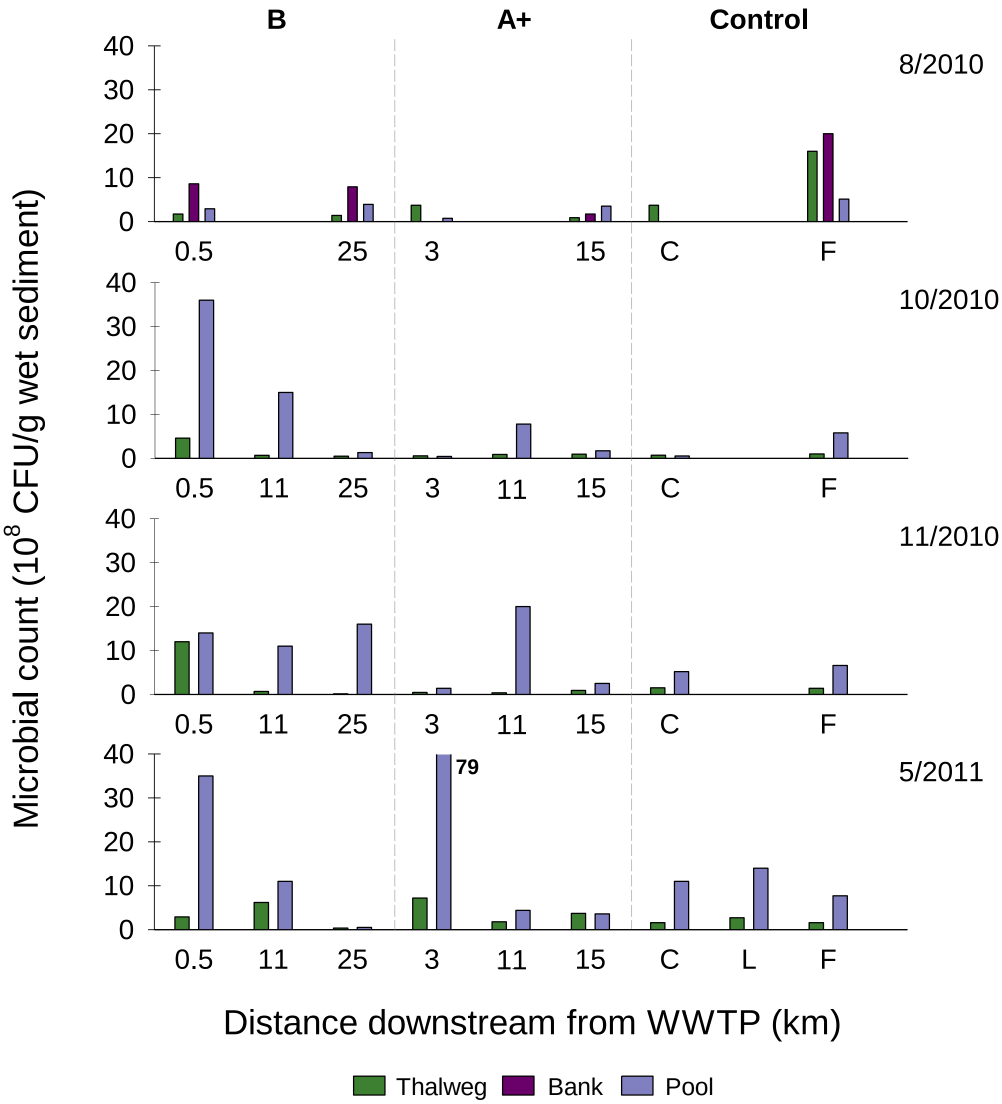


Figure 10 Heterotrophic plate counts from 20cm sediment cores collected at thalwegs (blue), banks (red), and pools (green). Cores were taken from thalwegs, banks, and pools, in the B class Lower Santa Cruz, and A+ Upper Santa Cruz at increasing distance from effluent discharge. Non-effluent control sites on the San Pedro included Charleston (C), Lewis Springs (L), and Fairbank (F)

Table 2 Spearman's rho values measuring correlations between hydraulic conductivity (K), sediment microbes (HPC), and environmental variables on the Lower Santa Cruz (B class), Upper Santa Cruz (A+ class), and San Pedro (control) Rivers.

	B class reach					A+ class reach					Control				
	4/2010	8/2010	10/2010	11/2010	5/2011	4/2010	8/2010	10/2010	11/2010	5/2011	4/2010	8/2010	10/2010	11/2010	5/2011
	K					K					K				
HPC		0.086	-.829*	-0.383	-0.486			-0.321	-0.886*	0.086					
Fines	-0.693**	-0.742**	-0.935**	-0.562**	-0.778**	-0.531*	-0.394*	-0.365	-0.283	-0.717**	-0.686**				-0.534**
Coarse		0.680**	0.908**	0.524**	0.768**		0.651**	0.301	0.216	0.706**					0.539**
Flow		0.080	0.282	0.641**	0.543**		-0.031	0.245	0.455*	0.281					0.271
Carbon	-0.091	-0.616**	-0.453*	-0.008	0.335	-0.312	0.120	0.299	-0.112	-0.069	-0.091				-0.157
Ammonia		-0.553*	-0.274	0.007	0.348		-0.220	0.087	0.023	-0.296	-0.204				-0.032
Nitrate	0.304	0.470*	0.564**	0.543**	0.331	0.127	-0.223	-0.172	0.179	0.455*	0.063				-0.037
TP	-0.37	-0.005	-0.334	-0.444*		-0.368	0.362	0.107	-0.338		-0.391				
ORP	0.207	0.465	0.533**	0.490*	0.101	0.123	0.023	-0.200	0.169	0.414*	-0.039				0.148
H2O temp	0.063	-0.329	-0.416*	-0.328	-0.175	0.087	0.153	-0.141	0.087	0.185	0.155				0.291
	HPC					HPC					HPC				
Fines		0.771	0.829*	0.500	-0.486			-0.486	0.600	0.486					-0.143
Coarse		-0.600	-0.829*	-0.400	-0.886*			0.543	-0.143	-0.486					0.086
Flow		-0.429	-0.736	-0.525	-0.395			-0.126	-0.880*	-0.273					-0.580
Carbon		0.543	0.714	0.357	-0.600			0.107	0.029	0.543					0.029
Ammonia		-0.553*	-0.274	0.007	0.348			-0.393	0.609	0.486					-0.314
Nitrate		0.470*	0.564**	0.543**	0.331			-0.821*	-0.371	-0.086					-0.829*
TP		-0.005	-0.334	-0.444*				0.107	-0.371						
DO		0.143	-0.314	0.524	-0.143			-0.750		-0.754					-0.829*
ORP		-0.696	-0.667	-0.619	0.029			-0.857*	-0.371	-0.314					-0.314
H2O temp		0.429	0.886*	0.571	0.116			-0.429	-0.600	0.232					-0.257

* p ≤ 0.05, ** 0.05 ≤ p≤ 0.1

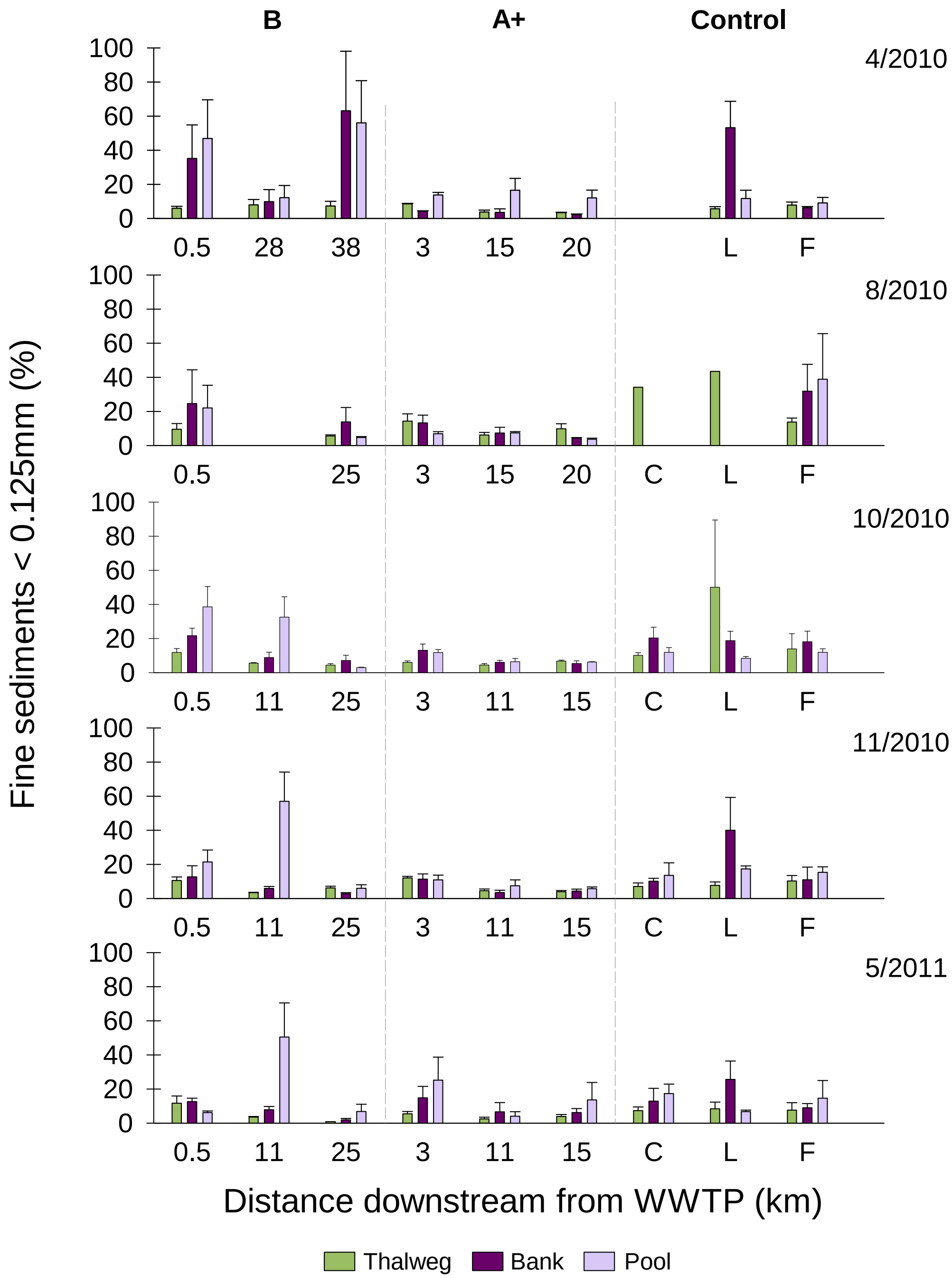


Figure 11 Percentage of fine textured sediments (0.125mm and smaller) measured in 20cm deep cores. Cores were taken from thalwegs, banks, and pools, in the B class Lower Santa Cruz, and A+ Upper Santa Cruz at increasing distance from effluent discharge. Non-effluent control sites on the San Pedro included Charleston (C), Lewis Springs (L), and Fairbank (F). Error bars represent ±1 standard error.

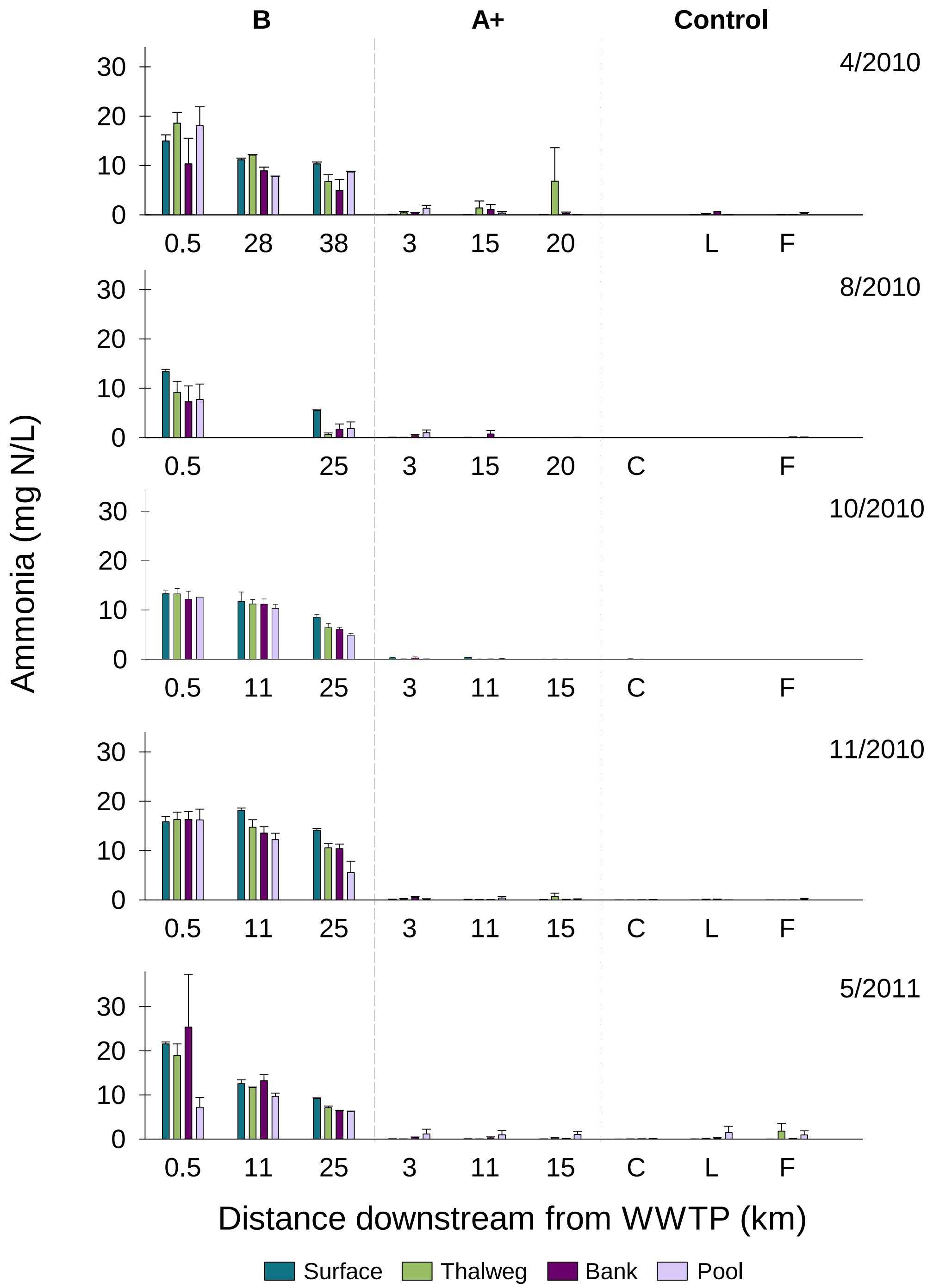


Figure 12 Ammonia concentrations in surface and pore water (thalweg, bank, and pool) of the effluent-dominated B and A+ class reaches on the Santa Cruz River. Non-effluent controls sites on the San Pedro River included Charleston (C), Lewis Springs (L), and Fairbank (F). Error bars represent 1 standard error. Missing distances/letters were not sampled.

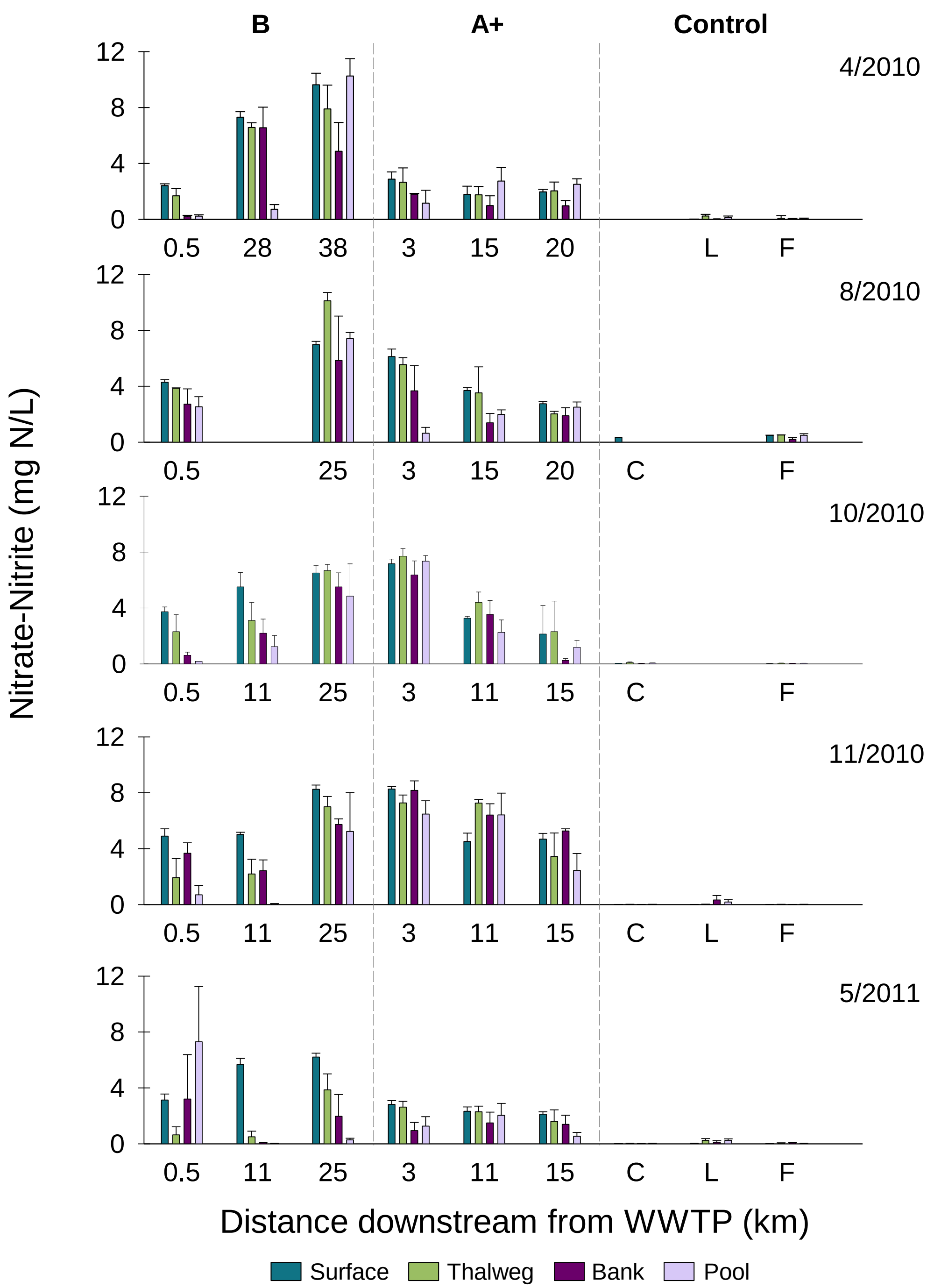


Figure 13 Nitrate concentrations in surface and pore water (thalweg, bank, and pool) of the effluent-dominated B and A+ class reaches on the Santa Cruz River. Non-effluent controls sites on the San Pedro River included Charleston (C), Lewis Springs (L), and Fairbank (F). Error bars represent 1 standard error. Missing distances/letters were not sampled.

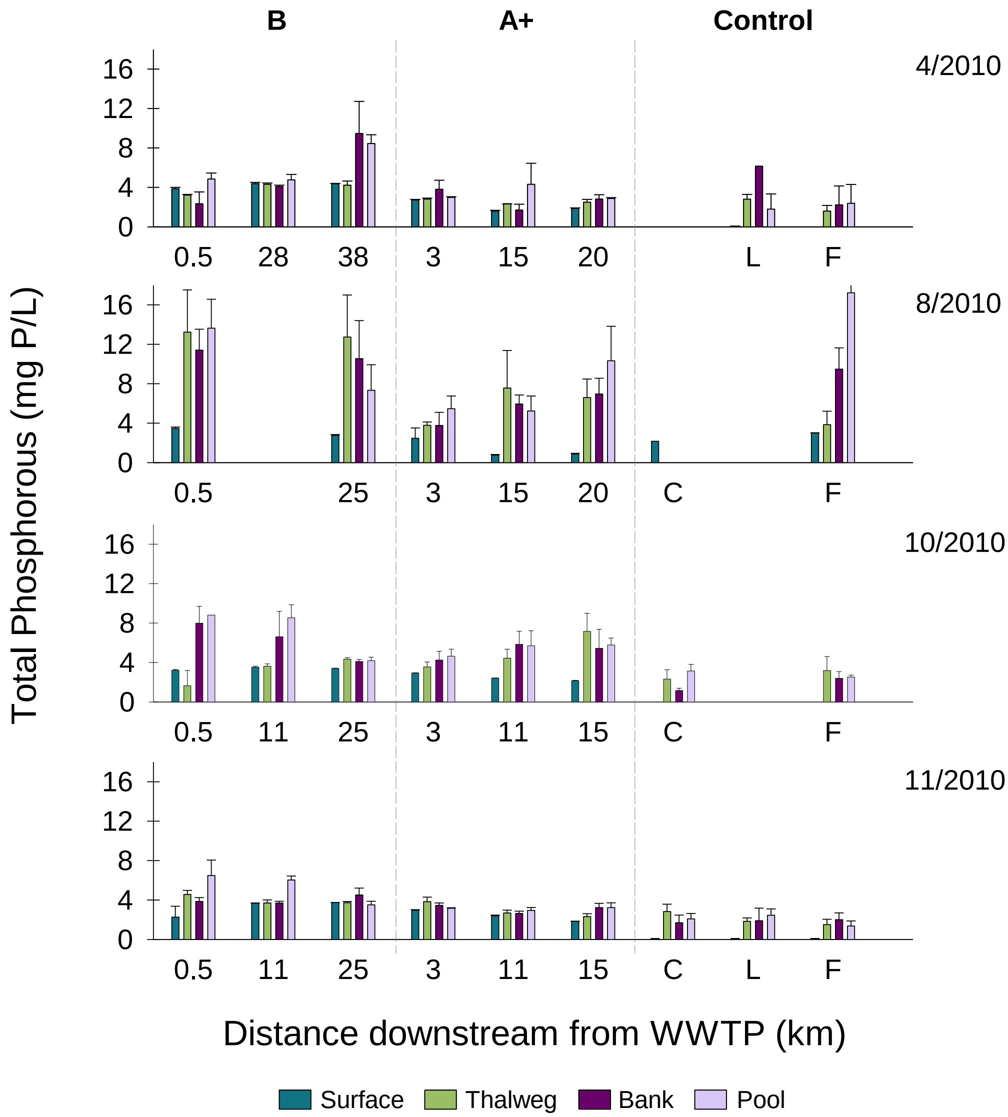


Figure 14 Total phosphorous concentrations in surface and pore water (thalweg, bank, and pool) of the effluent-dominated B and A+ class reaches on the Santa Cruz River. Non-effluent controls sites on the San Pedro River included Charleston (C), Lewis Springs (L), and Fairbank (F). Error bars represent 1 standard error. Missing distances/letters were not sampled.

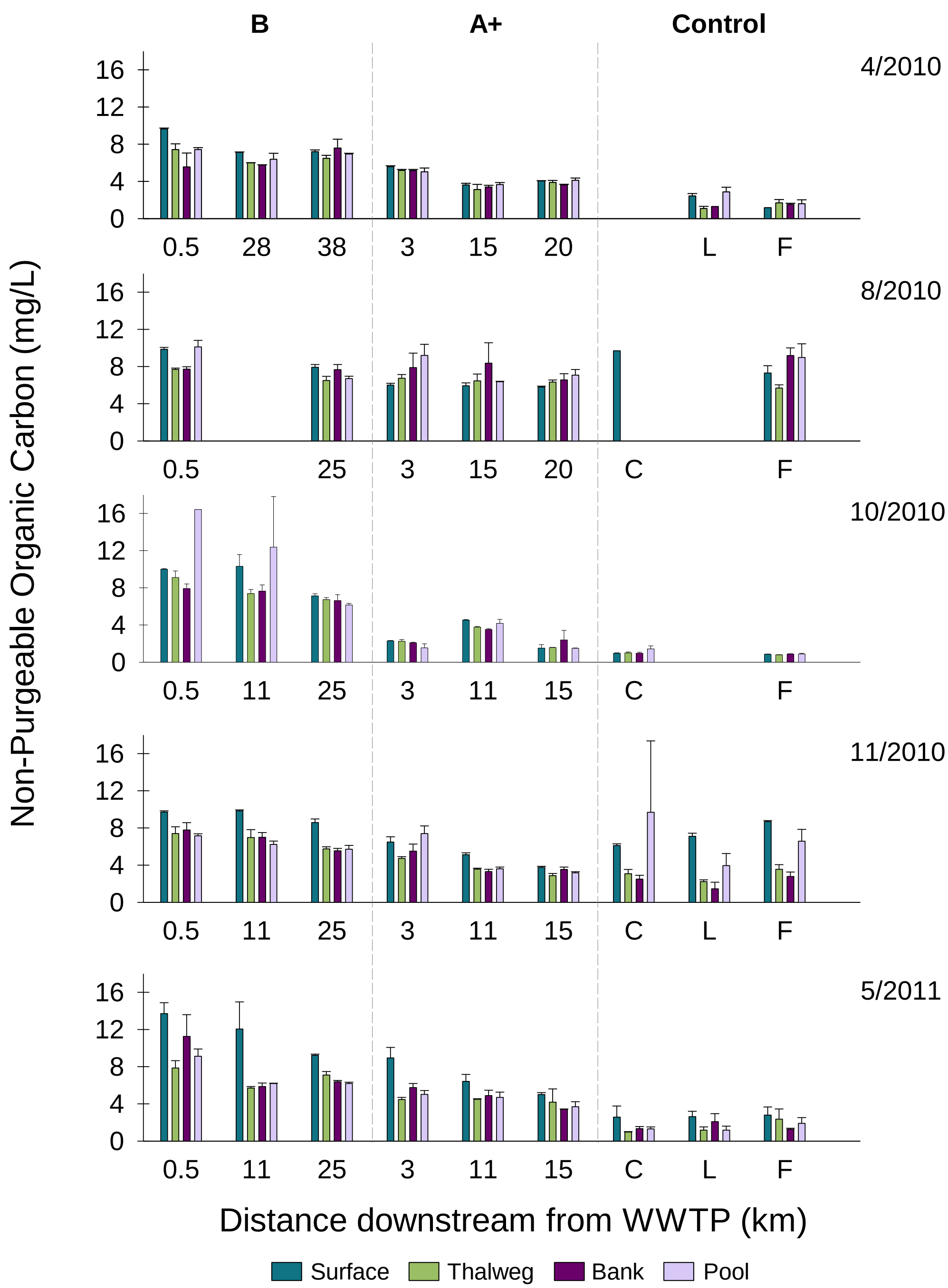


Figure 15 Organic carbon in surface and pore water (thalweg, bank, and pool) of the effluent-dominated B and A+ class reaches on the Santa Cruz River. Non-effluent controls sites on the San Pedro River included Charleston (C), Lewis Springs (L), and Fairbank (F). Error bars represent 1 standard error. Missing distances/letters were not sampled.

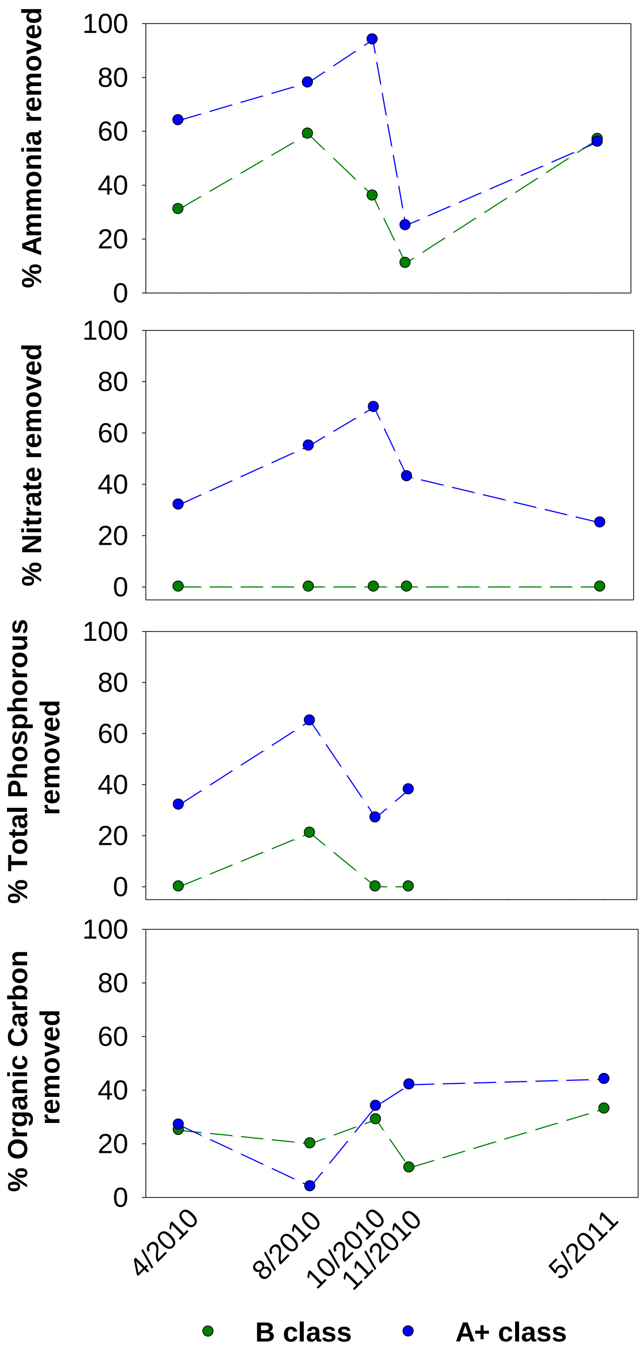


Figure 16 Percentage of nutrients removed from surface water between the effluent outfall and the site farthest downstream over the one year study period on the A+ (blue) and B class (green) reaches of the Santa Cruz River. After 4/2010, the B class study length was reduced by 10km and after 8/2010 the A+ class length was reduced by 5km.

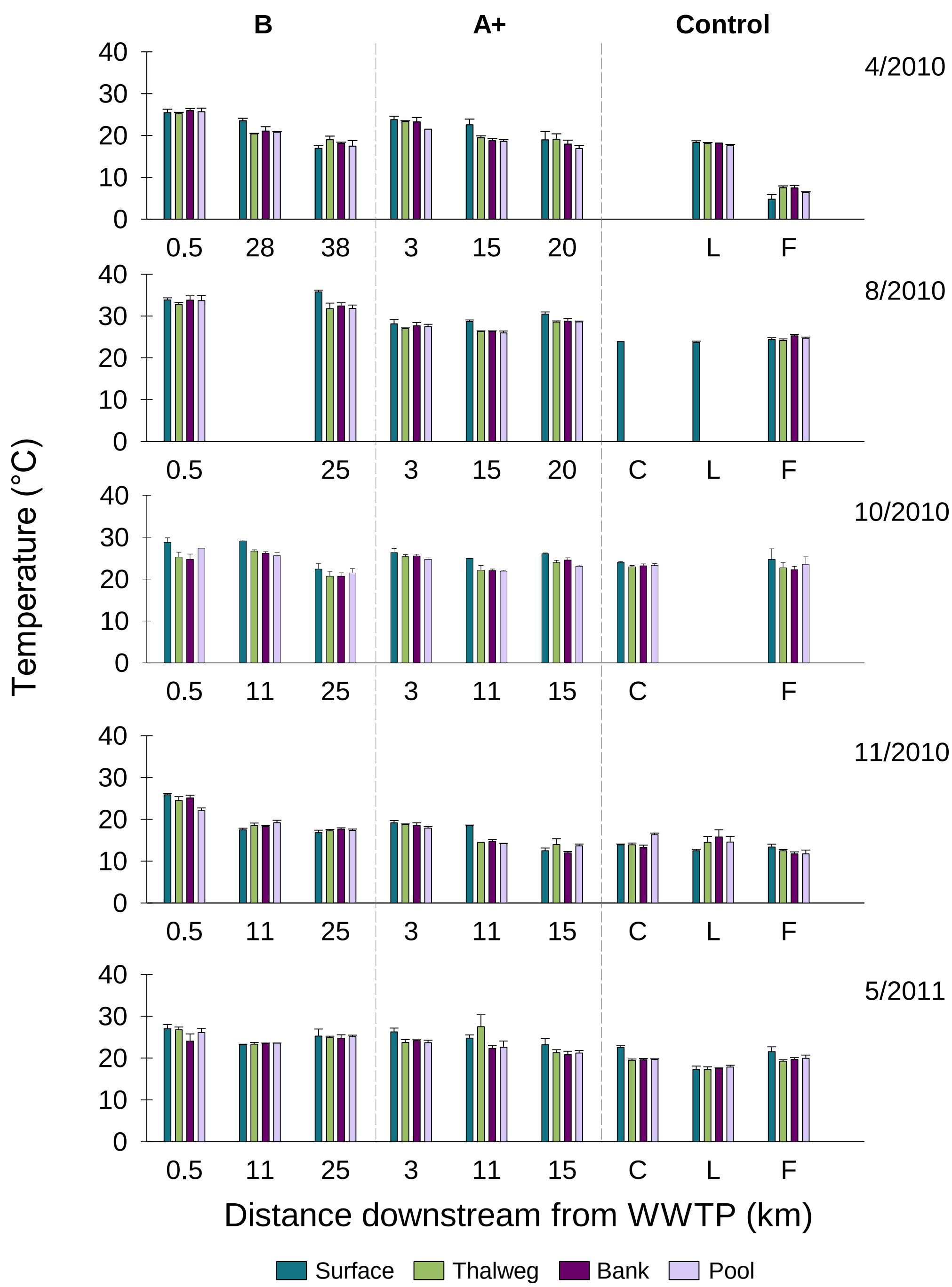


Figure 17 Temperature measured in surface and pore water (thalweg, bank, and pool) of the effluent-dominated B and A+ class reaches on the Santa Cruz River. Non-effluent controls sites on the San Pedro River included Charleston (C), Lewis Springs (L), and Fairbank (F). Error bars represent 1 standard error. Missing distances/letters were not sampled.

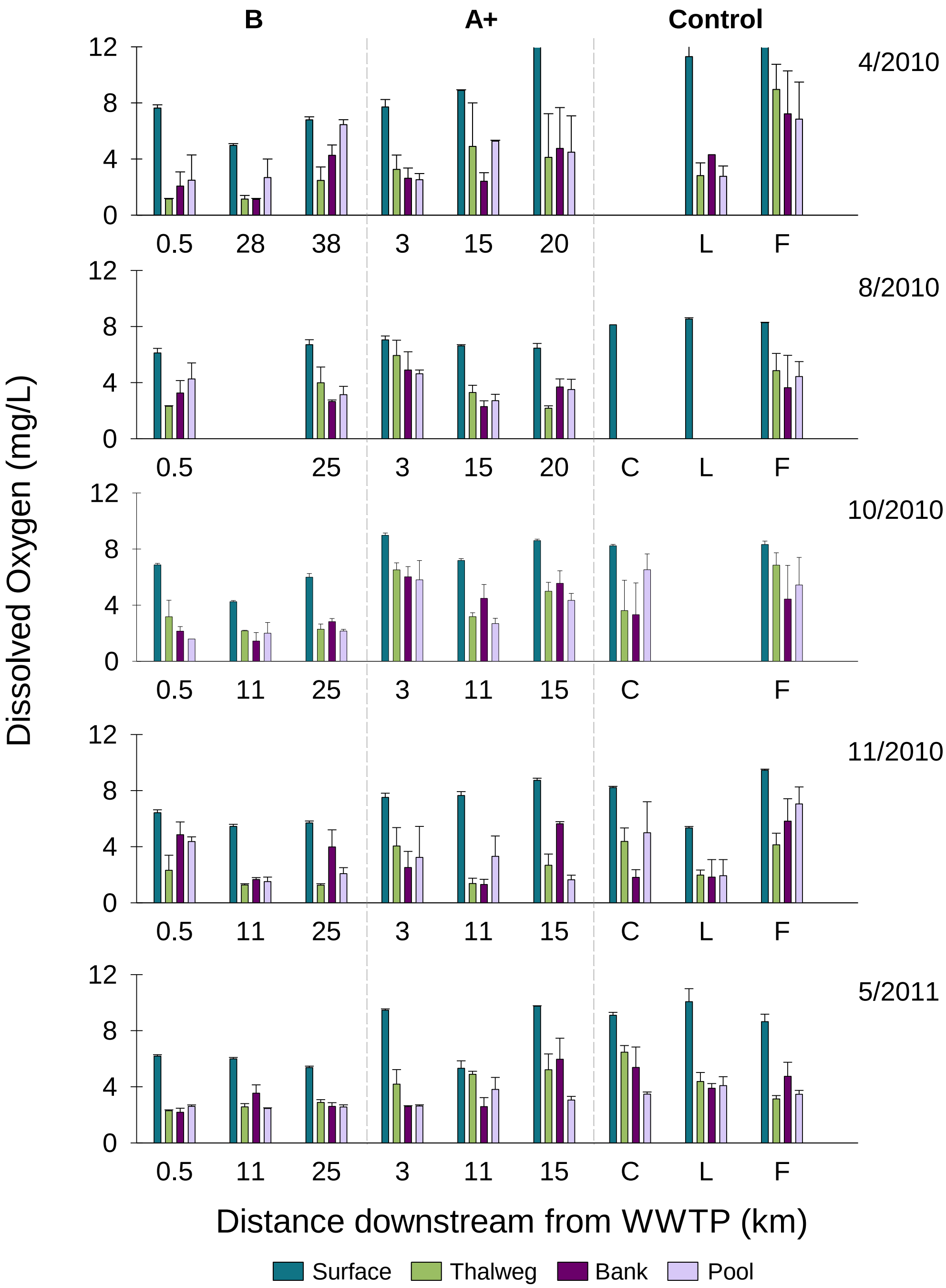


Figure 18 Dissolved oxygen measured in surface and pore water (thalweg, bank, and pool) of the effluent-dominated B and A+ class reaches on the Santa Cruz River. Non-effluent controls sites on the San Pedro River included Charleston (C), Lewis Springs (L), and Fairbank (F). Error bars represent 1 standard error. Missing distances/letters were not sampled.

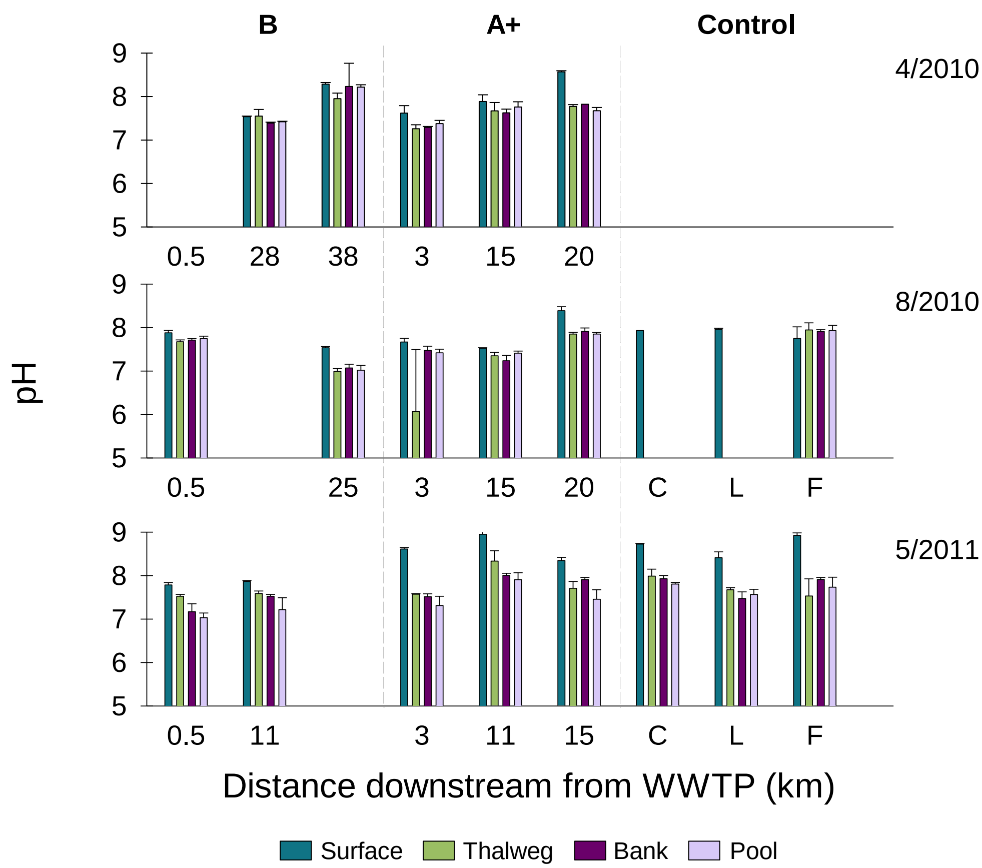


Figure19 pH measured in surface and pore water (thalweg, bank, and pool) of the effluent-dominated B and A+ class reaches on the Santa Cruz River. Non-effluent controls sites on the San Pedro River included Charleston (C), Lewis Springs (L), and Fairbank (F). Error bars represent 1 standard error. Missing distances/letters were not sampled.

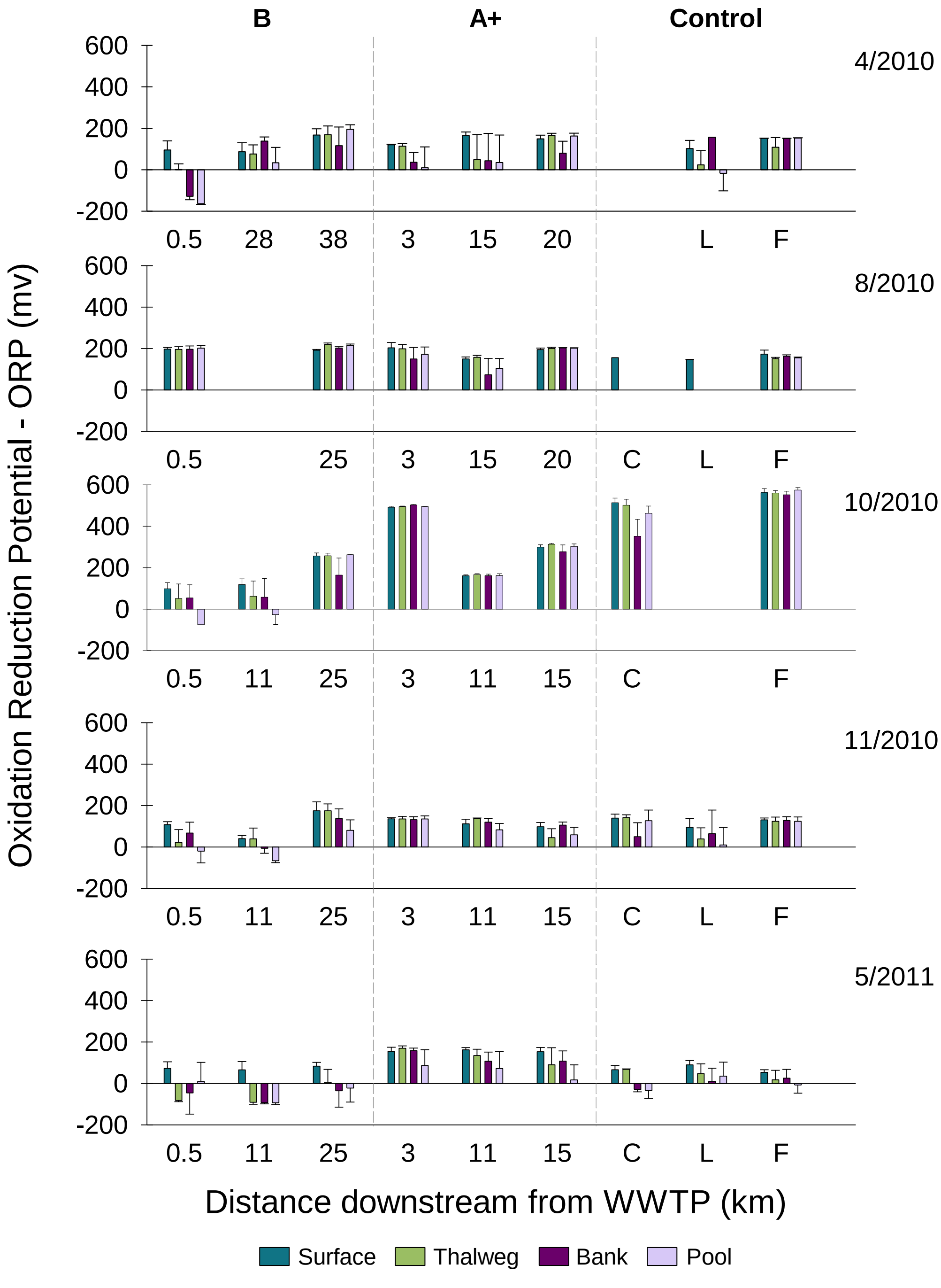


Figure 20 ORP measured in surface and pore water (thalweg, bank, and pool) of the effluent-dominated B and A+ class reaches on the Santa Cruz River. Non-effluent controls sites on the San Pedro River included Charleston (C), Lewis Springs (L), and Fairbank (F). Error bars represent 1 standard error. Missing distances/letters were not sampled.

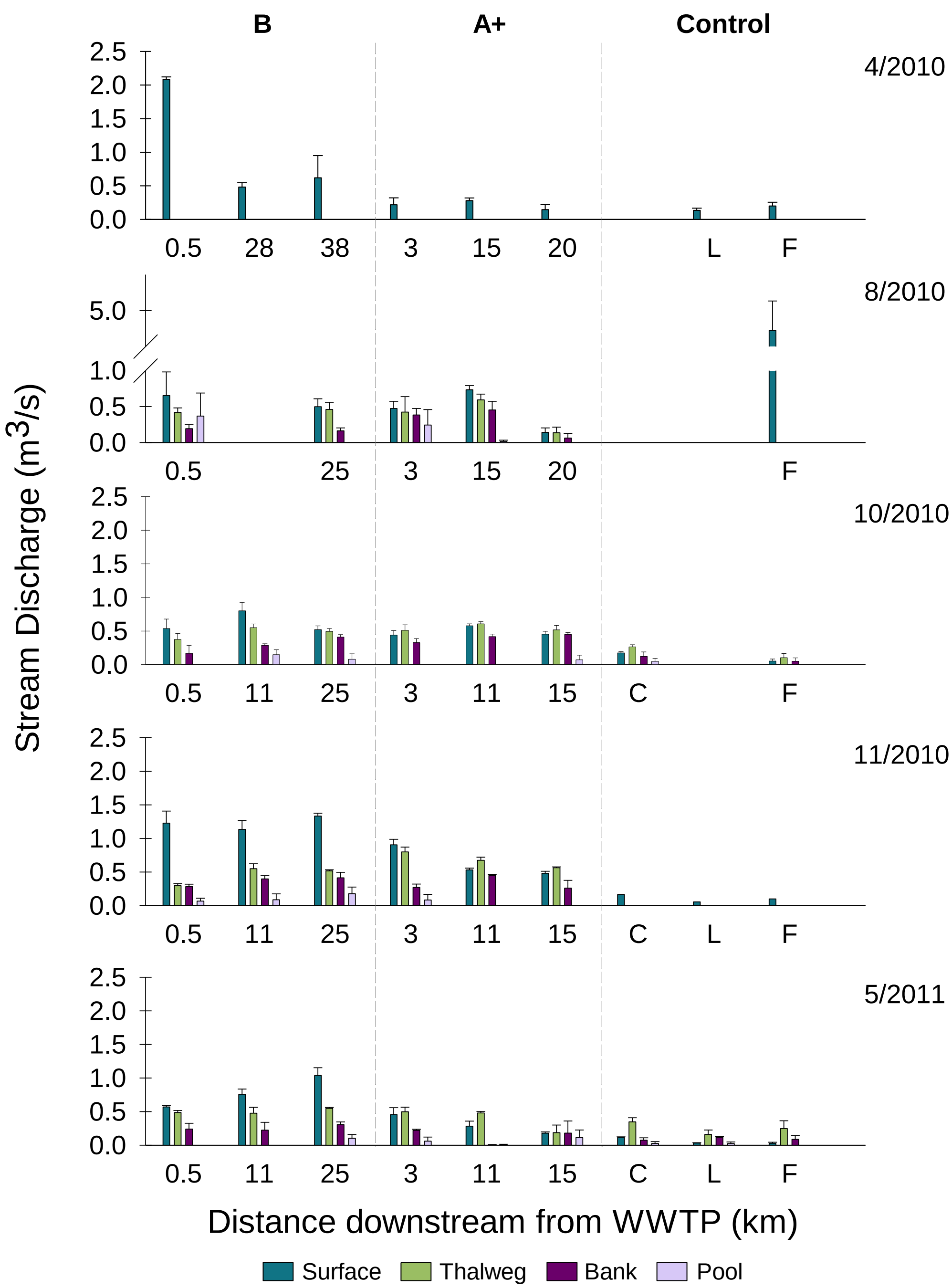


Figure 21 Stream flow measured by transect for surface water and at each piezometer cluster for thalweg, bank, and pool. Sites were located on the effluent-dominated B and A+ class reaches on the Santa Cruz River. Non-effluent controls sites on the San Pedro River included Charleston (C), Lewis Springs (L), and Fairbank (F). Error bars represent 1 standard error. Missing distances/letters were not sampled.

2. BALANCING CLOGGING WITH ENHANCED RECHARGE

Introduction

In the City of Tucson, AZ, wastewater treated and discharged by the Roger and Ina Roads Waste Water Treatment Plants (WWTP) flows in the Santa Cruz River for approximately 40km. While this water amendment restores surface flow to the river and supports riparian habitat, it also serves to recharge the aquifer within the Lower Santa Cruz River Managed Recharge Project (MRP), allowing the U.S. Bureau of Reclamation to meet water settlement obligations (Bureau of Reclamation, 2012). Yet, the situation is not so straightforward. Most, but not all, of the surface flow in the Santa Cruz falls within the Tucson Active Management Area (TAMA). Within this boundary, the City of Tucson and the Bureau of Reclamation receive recharge credits for the water that infiltrates to the aquifer. These credits allow the agencies to withdraw water from the aquifer at a later time. The recharge credits for effluent only allow half the volume of water that was stored to be withdrawn, and recharge outside of the Management Area is not counted. Currently, the MRP stores less than half of its allowed recharge credits (Bureau of Reclamation, 2012).

Under these circumstances, a potential water source is lost through the Santa Cruz, and managers are pursuing options to utilize the full extent of their water resources. One option would be to divert the effluent from the river and recharge it directly to the aquifer. With the water table sitting 200ft below ground in the area (Bureau of Reclamation, 2012) this action would undoubtedly cause a high percentage of mortality in the surrounding riparian vegetation that is sustained by surface effluent. Fortunately, another option is being investigated.

In January 2011, the Bureau of Reclamation and its partners began construction of the Enhanced Recharge Demonstration Project (ERP) in an effort to increase the amount of surface water infiltration in the Santa Cruz River. Two small, secondary channels were excavated into an abandoned channel and water was diverted from the active channel to create three active channels (Figure 22). The project ran for 5 months, and this study spanned the first four months. This setting not only provided a unique opportunity to study the development of clogging in a newly created river, but flow from the active channel could be cut off, allowing the secondary channels to dry and reset the clogging process as needed. Our specific questions were: 1) *Did hydraulic conductivity change over time with treatment? 2) Did sediment biomass change over time with treatment? 3) Were there trends in physiochemical parameters?*

Study Area

The Bureau of Reclamation’s Enhanced Recharge Project (ERP) site is located on the Santa Cruz River (SCR) near the town of Marana, AZ (Latitude 32°25'27.78"N and Longitude 111°12'50.40"W). This site was selected by BOR based on ease of access, channel morphology, and sediments that would favor recharge. Two secondary low-flow channels were dug along a bend in the main channel using heavy machinery, and a flume system was installed. Water was added to the new channels on January 28, 2011, at a flow rate of 051cms (1.8cfs). Three maintenance events were conducted during the study: The first occurred after the ERP had been in operation for 60 days. The channel was dried over 15 days, then scraped and ripped using a John Deere 4240 tractor with 36-inch ripper. The second maintenance occurred 30 days later, when the channel was dried over 12 days, then ripped twice. The final maintenance occurred 29 days later and was left to dry for 8 days. The project ended on July 5, 2011, when monsoon storm flows washed out the channels and flumes.

Three transects were established, approximately 100 meters (m) apart, on the southernmost low flow channel, and a fourth reference transect was set on the SCR main channel (Figure 22). Two sites were established along the SCR transect; one along the bank and one along the thalweg, or center of the channel. The ERP did not have a distinct thalweg, so the center and bank sites were considered replicates. Sampling took place on January 29, 2011, at the start of the project; February 26, after one month of development; and April 16, after the first drying, ripping, and rewetting treatment. Samples were not collected after the second and third maintenance events due to schedule conflicts.

Methods

Hydrology

Flow rates were measured with a flow meter, with average velocity recorded at several vertical points along each transect. When flow was too slow for the meter to detect (<0.3 feet per second) the float method was utilized (Gordon et al., 1992). Hydraulic conductivity (K) was calculated as an indication of infiltration rates (K is a measure of the resistance to the flow of water through interstitial spaces). Shallow in-stream peizometers (modified from Chen, 2004) were installed each trip to measure vertical hydraulic conductivity of the sediments using a falling head test (Chen, 2004). The piezometers were constructed of clear, 4 cm inner diameter pvc pipe cut to 122cm lengths. Piezometers were installed in sets of three at depths of 10, 15, and 20cm below the sediment surface at each site (thalweg and bank) totaling 18 piezometers on the ERP and 6 on the SCR. Though clogging is often observed as a surface phenomenon within the first few centimeters, previous research on the Santa Cruz had detected clogging layers developing below 10cm (Treese et al., 2009); these methods allowed us to differentiate between 0-10, 10-15, and 15-20cm. Piezometers were installed manually with a mallet and left to equilibrate for approximately an hour. After this, the distances from the top of the pipe to the water level inside and outside the pipe were recorded and clean surface water was slowly added to fill the pipe full. The time it took for the water level in the pipe to fall 1 cm was recorded. This measurement was repeated a total of three times and the value averaged. In places of low infiltration this measurement was abbreviated by setting a cut-off time of 10 minutes and the time recorded as >10 minutes.

Sediment characterization

Following infiltration measurements, the 20cm pipe was carefully removed from the sediments to provide a sediment core sample. The sediments were collected in a bag and kept on ice until analysis. Notes of visual observations such as surface algal biofilms, dark iron-reducing layers, gas bubbles, or high organic matter were recorded.

Sediment bacteria were plated and counted as an indication of biological clogging. A homogenous subsample of the sediment core was used for biological analysis within a week of collection. Heterotrophic plate counts were conducted using Standard Methods Spread Plate Method 9215C (American Public Health Association, 2005). In preparation, wet sediments were packed into 50ml sterile centrifuge tubes and left to stand overnight so excess water could be poured off. Next, 50g of sediment were transferred into sterile 500ml plastic bottles. For a 1:10 dilution, 450ml of sterile phosphate buffered solution were added to each bottle which was vigorously agitated by hand for five minutes to dislodge attached cells. Promptly after agitation, 100 µl of the suspension was transferred aseptically to a set of serial dilution tubes containing 900 µl of sterile phosphate buffer. Corresponding duplicate plates of R2A agar received 100 µl from the dilution tubes and were spread dry with sterile glass rods. Inoculated plates were incubated at room temperature for 72h, or until colonies were easily countable. Plates containing 30-300 colonies were counted and recorded. Initial wet sediments were weighed, oven dried, and re-weighed to determine the number of colony forming units (CFUs) per gram of dry sediment.

The remaining portion of the core sample was oven dried and sieved to conduct texture analysis (modified from Gee and Or, 2002). Sediment texture was monitored throughout the study as a physical factor that regulates hydraulic conductivity. At each sampling time, the % gravel (> 2mm) fraction was determined and 75g of soil (< 2mm) was reserved to determine silt and clay content using the hydrometer method. Sand fractions were determined after hydrometer measurements by wet sieving the sample through a 63 µm sieve. The sample was oven dried and then sieved through a stack of sieves to yield very coarse (1000-2000 µm), coarse (500-1000 µm), medium (250-500 µm), fine (125-250 µm), and very fine (63-125 µm) sand fractions.

Water chemistry

Water chemistry from surface water and porewater was examined as an indication of biological activity in the sediments. A surface water grab sample was collected in the center of each transect and a sediment water sample was collected at each cluster of piezometers using a pore water extractor. The pore water extractor (M.H.E Products) had a screened zone at one end and a sampling port at the other, and after being pushed into the sediment to the 20cm depth, pore water was extracted with a peristaltic pump. Dissolved oxygen (DO), pH, oxidation-reduction potential (ORP), and temperature were measured on site using portable multi-parameter meters (Oakton DO6, and Hanna Combo pH & ORP). Water samples were collected in acid washed plastic bottles for further laboratory analyses. In accordance with Environmental Protection Agency regulations (40 Pt. 136.3), samples were transported on ice, stored at 4ºC, and analyzed for nutrients within 48h. Prior to analysis, the bottles were centrifuged at 5000rpm for 10m to remove particles. Subsamples for ammonia, nitrite/nitrate, and phosphate (as orthophosphate) were frozen until analysis, and non-purgeable organic carbon (NPOC) subsamples were acidified with hydrochloric acid to a pH of 2 and stored at 4ºC until analysis. NPOC is a measure of total organic carbon where inorganic and some volatile organic carbon is removed from the sample. Analyses were performed by Arizona State University Goldwater Environmental Lab research specialists.

Analysis

Data were log or square root transformed prior to statistical analysis. Pearson's correlations were used to show the relationships of conductivity data with bacterial and texture variables. Welch's analysis of variance (ANOVA) was applied to test for differences in conductivity between the three sediment depths (alpha level of 0.05) A repeated measures ANOVA was used to test for differences in bacterial abundance, followed by Tukey's Honestly Significant Difference post-hoc test, with a Bonferroni correction. Analyses were performed with the software SPSS (Release 19.0, SPSS Inc.).

Results

Did hydraulic conductivity change over time with treatment?

Conductivity declined over time, as expected, but was restored after drying and scraping treatments. At the start of the project, conductivity in the ERP was low, at a level similar to a clogged bank on the main channel of the Santa Cruz (Figure 23). The SCR thalweg was two orders of magnitude higher than the bank and ERP channel. However, over the first month, conductivity in the ERP declined to levels even lower than measured at the SCR bank. In April, the ERP channel was dried and the surface scraped to remove a 3.8cm thick layer of fines. After water was released back to the channel, conductivity measurements returned to levels slightly higher than January. There was a significant difference in conductivity between months ($F_{(2, 45)} = 7.882$, $p = .001$), and a Tukey post-hoc test revealed that conductivity was significantly higher in April after the channel was dried and scraped (0.0033 ± 0.003 cm/s, $P = 0.001$) than in February (0.0005 ± 0.0005 cm/s, $P = 0.249$). There were no significant differences detected between January and February or January and April. While an ANOVA showed no significant difference between the different depths sampled during the study (results not shown), a more detailed examination of the ERP conductivity profile shows interesting patterns (Figure 24). In January the sediments were so compacted that it was difficult to install the piezometers. This compaction may have contributed to restricted water movement through the top 20cm. The higher conductivity at T2 20cm in January may have been due to larger gravel, and T3 was not measured due to delays caused by gravelly and compacted sediments. After the drying treatment in April the sediments became loose and soft, and conductivity was greatly improved at all depths measured. However, residual spots of low conductivity remained (Figure 24: T2, T3).

Did sediment biomass change over time with treatment?

Sediment bacteria counts increased exponentially during the first three months of the project (Figure 25), though exponential growth was not seen in the SCR. The ERP growth pattern was surprising because in January the sediment bacteria had only one day between water addition and sample collection to establish, yet their numbers were slightly greater than the SCR thalweg, and slightly less than then SCR bank. Also, at the end of March, the ERP was dried over a period of two weeks and scraped, but this disturbance did not cause a decline in bacteria counts. During April sampling, the channel had only been wetted for a few days before sample collection. The large error bars in April should also be noted; only half of the samples had increased above February while the remaining half was in the range of February counts. A repeated measures ANOVA found a significant difference in bacterial counts between sampling times ($F_{(2, 10)} = 6.252$, $P = 0.017$), and a post hoc test determined that the difference between January and April was the only significant difference ($p=0.013$). Though correlations between bacteria and conductivity became stronger over time, they show only a weak negative association (Table 2).

Qualitative measures of sediment biomass were also noticeable in the ERP. In January, the ERP had no signs of biological activity, but by February, non-filamentous algal mats were growing and thick sludge layers were building up on the sediment surface, increasingly so towards the downstream flume. Sediment cores were showing black layers as well (iron sulfide deposits from bacterial metabolic byproducts). At this point the primary production was sufficient to support an abundant community of amphipods (scuds) and chironomid larvae (blood worms), both of which are pollution tolerant invertebrates. In April, photosynthetic mats were growing back, indicating that the biotic community recovers quickly after disturbance in the ERP.

Were there trends in physiochemical parameters?

Sediment texture. The ERP sediment texture most closely resembled the SCR bank with its finer textures although it did have a higher percentage of gravel than the SCR (Figure 26). The drying, scraping, and ripping treatment in April resulted in a decrease in the percentage of fines in the ERP. Variations in the SCR bank texture are likely due to the heterogeneous morphology of banks and smaller sample size (only one transect and core). Similar to biomass, the correlation between percent fines and conductivity grew over time, but it was a weak negative association (Table 2).

Stream Flow. In contrast to the Santa Cruz River, flow in the ERP channel was too low to measure during this study (Figure 27, B). An average flow of 4 cfs was measured in the flume, but because effluent discharge from the WWTP varies throughout the day, zero-flow point measurements were frequently recorded. Later in the project, flow rates were increased.

Water chemistry. In many respects, the physical and chemical profile of ERP channel resembled the SCR, with some interesting exceptions. Dissolved oxygen (DO) decreased in the SCR over the three months as temperatures warmed, but in the ERP surface water, DO readings were extremely high (Figure 27, A). These readings coincided with low stream flow and high algal photosynthetic activity. In the ERP sediment porewater, DO was high in January, but dropped over the months, indicating that oxygen was either being consumed by bacteria or not being delivered into the deeper sediments. From the water quality results (Table

3) there were a few trends of note. Oxidation-reduction potential (ORP) stayed unexpectedly high in the ERP sediments, never dropping below 140mV. NPOC, a measure of organic carbon, decreased from 17 to 13mg/L in February, and then to 8mg/L after the April drying. Nitrates, however, did not decrease in the ERP sediments as they did in the SCR sediments.

Discussion

Did hydraulic conductivity change over time with treatment?

Hydraulic conductivity on the ERP was relatively low to start, matching that of the stagnant SCR bank, but over the course of the first month it continued to decline. The drying and ripping treatment effectively restored conductivity to rates greater than the initial levels. Physical processes were evidently responsible for the low initial conductivity. The ERP channel had been constructed by heavy machinery, rather than flowing water, leaving the sediments densely packed from the weight. Pitt and others (1999) found that infiltration rates in sandy soils were greatly reduced after compaction by construction activity.

Fortunately, the drying and ripping treatment in April was very effective at loosening the compacted sediments and restoring conductivity. The difference in conductivity patterns of February and April indicate that the top 10 cm were highly clogged, with slow water movement through the subsequent depths. The drying treatment left the sediments permeable to the 20cm depth, though there were residual clogged areas that did not seem to be affected by the treatment. Even though conductivity rates were improved on the ERP, April conductivity was still in range with the SCR bank and far below that of the thalweg. There were clearly other variables limiting the conductivity of the project.

Did sediment biomass change over time with treatment?

Bacterial numbers rose exponentially during the course of the study and were not inhibited by the drying and ripping process. The newly constructed ERP channel had clean, bare sediments, but bacterial counts were surprisingly high for these newly wetted sediments. This suggests that sediments are rapidly colonized with the addition of effluent. After one month, the ERP sediments were no longer barren. Like the SCR bank, the sediments had built up considerable amounts of algal mats, organic sludge layers, and black metal oxide deposits. Bacterial abundance had reached levels much higher than the SCR, however. While bacteria counts rose sharply in the ERP, there was not a similar trend in the SCR. It was clear that conditions in the ERP were promoting biological growth. The lack of scouring flow appeared to be the main influence, as it allowed the extensive buildup of algal mats and sludge in the ERP. Bacteria are known to feed off of exudates released by algae (Haack & McFeters, 1982) so the algal mats and sludge could serve as additional sources of carbon to fuel bacterial growth.

After the disturbance in April, sediments had the highest bacterial counts of the study, indicating that drying did not inhibit bacterial abundance. McKew and others (2011) studied the bacterial community of a salt marsh by extending the normal tidal desiccation period to several weeks. After rewetting the site, they found bacterial activity increased sharply. They also discovered a change in the bacterial community, where particular species were able to increase their abundance under the new disturbance pattern. Drying the ERP may allow desiccation-resistant species to dominate the sediments and drive bacterial counts higher.

The biological developments over the first month coincided with a drop in conductivity. While there was also a slight buildup of silt over the first month, biology was the main variable that had changed during this period. This pattern supports the hypothesis that biological clogging would be promoted in the ERP. However, the disruption in April presents a more complicated picture; after the channel is dried and rewetted, conductivity was at its highest, yet bacteria were also at their greatest abundance. It appears the relationship between bacterial abundance and conductivity rates in the ERP is not straight forward. Laboratory column experiments have demonstrated that increased biomass decreases conductivity rates (Mitchell & Nevo, 1964; Vandevivere & Baveye, 1992a; Wu et al., 1997).

While biological clogging is well-studied under laboratory conditions, it is rarely studied in the field setting where a multitude of other variables are interacting. It is possible that after water was added back to the channel in April, the loosened sediments allowed more nutrients and oxygen to be delivered deeper, allowing more bacteria to grow. Drying can also affect the quality of organic matter. One study reported that after wetlands were allowed to dry, the organic matter fractured into smaller components were more easily utilized by the bacteria upon rewetting (Sommer, 2006). Ripping could have introduced organic matter deeper into the sediments to be decomposed by bacteria, allowing more growth. Finally, temperature may have been a confounding variable; algal and microbial growth rates are temperature dependent, and April was approximately 10ºC warmer than the previous months. These conditions can explain why bacteria grew so well after the disturbance, but not why the relationship to conductivity changed after drying. The correlation between bacteria and conductivity was not strong, but of the variables considered, biological clogging is the most likely cause of the decrease in conductivity.

Given the small sample size and only sampling one post-drying event, it is premature to make strong conclusions about the bacterial counts, but they may not be the most informative measure of biological clogging for the ERP. Other measures of biological activity that could be investigated include chlorophyll a to quantify algal abundance in the sediment, polysaccharide determination to quantify biofilm development, or extracellular enzyme activity of sediment bacteria.

Were there trends in physiochemical parameters?

Fine-textured sediments are another physical variable that can lead to clogging. Though the fine sediments did not change much throughout the study, the ERP channel had a higher percentage of clay and silt than the SCR bank. The ERP channel was constructed in the active floodplain of the SCR, where fine sediments are deposited during floods but are not continuously scoured like the active channel. Fine-textured sediments fill in the pore spaces that water must move through to infiltrate downwards, so fines lead to lower infiltration rates (Brunke, 1999). The fines probably worsened the effects of compaction, and over the first month silt increased slightly. In the SCR, fines only tend to build up in slow moving banks, while the thalweg maintains a corridor of scoured sand and high conductivity. The ERP channel lacked a thalweg, having uniformly distributed fines and conductivity. Ripping and scraping the channel successfully restored and improved conductivity, but did not measurably decrease the percentages of fines. The ERP may not be capable of attaining the higher hydraulic conductivity rates seen in the SCR thalweg until flooding scours out more of the silts and clays.

The ERP also had a higher percentage of gravel than the SCR, and while texture size tends to be directly related to conductivity, Brakensiek and Rawls (1994) concluded that rock fragments in soil will reduce conductivity. Rocks are assumed to have low porosity, or zero conductivity, so soils containing high percentages of gravel will have less volume for more porous soils, leading to lower conductivity. This may help explain why the higher gravel content in the ERP did not have higher conductivities.

Flow rates were an important reason that conductivity rates in the ERP declined. This study and our previous findings (unpublished) on the SCR show that thalwegs, with strong flow and scoured sandy sediments, usually have the highest conductivity measurements. Flow in the ERP channel was usually not measurable during low flow conditions. While the effluent discharge cycles through low and high flows through the day, the high flows must not have been strong enough during the first three months to scour out fines and prevent buildup of material on the sediment surface.

While low flow rates could potentially allow the surface water more time to infiltrate, conductivity rates dropped lower than the bank of the SCR during the first month. Low flow promotes biological activity, such as photosynthetic mats and anaerobic sediments that entrap metabolic gasses, as well as physical properties like the buildup of sludge layers and retention of fines. These can act as barriers at the sediment surface, preventing water from entering the sediments. Flume experiments have determined that sheer stress values less than 0.056 accelerate clogging (Schalchli, 1992). For river regulating projects, Schalchli also suggests that areas with varied geomorphology help reduce clogging layers.

Finally, water quality parameters indicated that some biological processes in the ERP differed from the SCR. Even though ERP surface water DO readings were quite high in April (due to algal photosynthesis), readings were low in the sediments; because this coincides with high bacterial counts, it reflects high metabolic activity in the sediments. Interestingly, high ORP readings are maintained in the sediments throughout the study, indicating that anaerobic metabolisms were not favored. The SCR banks usually maintain much lower ORP readings than surface water, as they promote anaerobic conditions and metabolisms. Nitrates declined in the SCR sediments as temperatures warmed in April, but they did not decline in the ERP. Under low oxygen conditions, bacteria convert nitrate into nitrogen gas, where it is lost from the system. Denitrification and other anaerobic processes would be inhibited by sediment disturbance that introduces oxygen. The drying and scraping combined with a large increase in the amount of oxygen-rich water moving through the sediment may explain why nitrates remained high in ERP sediments. The use of effluent and drying cycles could alter sediment water chemistry, but further research would help clarify the effects.

Conclusions

While the duration of the ERP pilot study was short, a number of patterns emerged that may be useful in guiding future studies in improving infiltration:

- Low flow conditions in the ERP promoted high biological activity and retention of fine particles, leading to declines in hydraulic conductivity.
- Texture may be a limiting factor on conductivity - flooding or flushing the ERP may help reduce fines and improve overall conductivity.
- Low conductivity can be overcome by drying and ripping, but the time between channel disruptions could potentially be extended if flow in the channel were increased.

•There was evidence for biological clogging before treatment/maintenance events, but not after treatment. Further research is needed to clarify this relationship.

•The small sample size and short sampling period of this study increase uncertainty, leaving these as preliminary conclusions.

Conclusions from this study could be applied to future scenarios for the Santa Cruz River. Water use projections indicate that treated wastewater will be increasingly utilized in the urban setting, leaving less volume available for discharge to the river. If the amount of water discharged to the Santa Cruz is significantly reduced in the near future, as is projected, then low flow conditions in the channel could become the norm. Under this scenario, one would expect to see more clogging conditions and poor infiltration in the river. If future infiltration studies are conducted with the ERP, it would be interesting to use the two ERP channels as separate treatments over the same period to determine if one combination of drying, scraping, and ripping is more effective than another. Examining treatments over the same time period would reduce interfering variables like temperature increases or changes in the water quality being discharged.

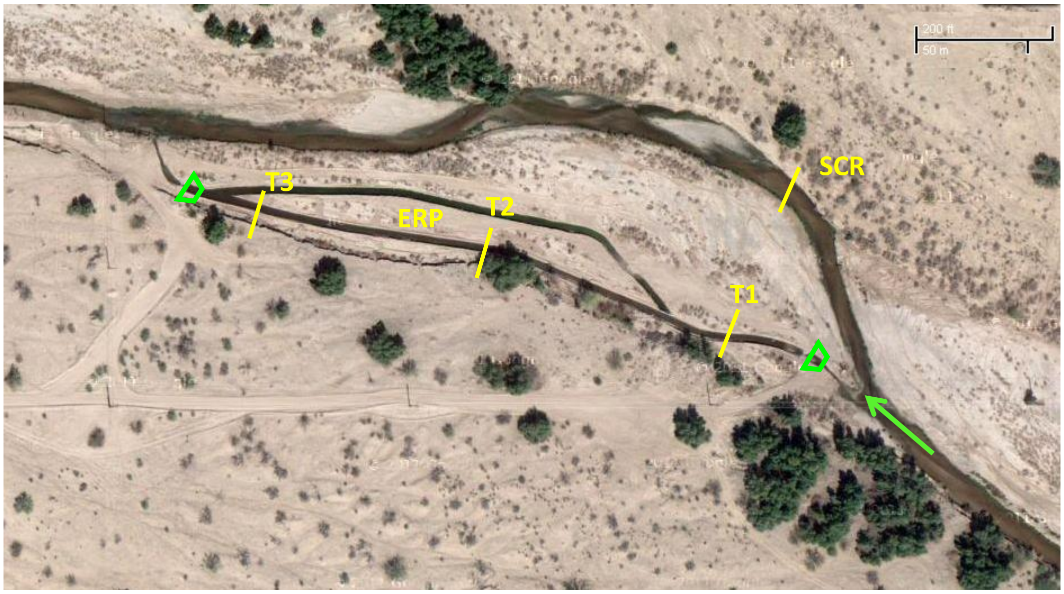


Figure 22 Main channel of the Santa Cruz River and two previously abandoned low flow channels used as the site of the Enhanced Recharge Project. Yellow lines indicate locations of transects, and green boxes are the flumes used to measure flow diverted from the main channel into and out of the secondary channels. Image from Google Maps, 8/2011.

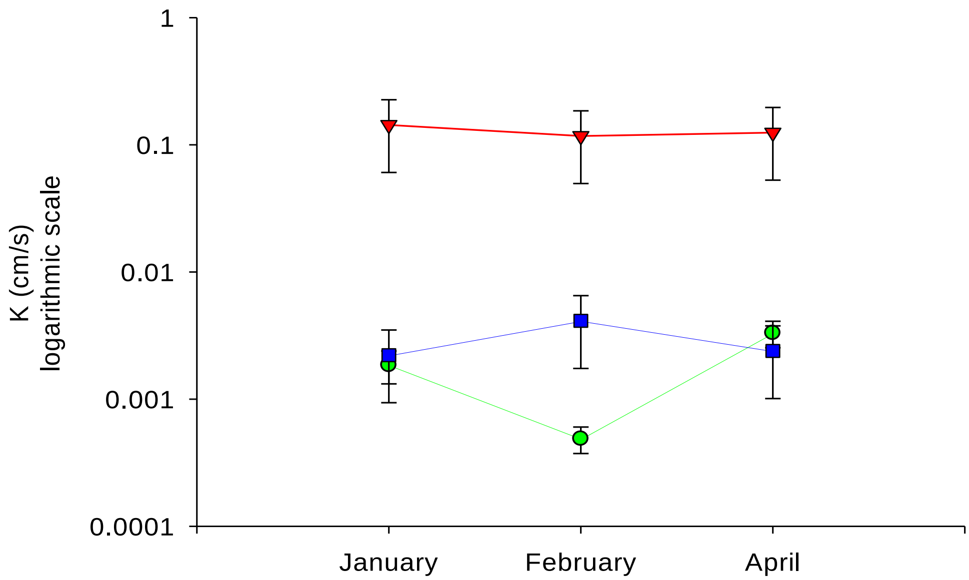


Figure 23 Average hydraulic conductivity of the ERP channel , SCR bank , and SCR thalweg during 2011. Log scale is used because the thalweg conductivity was much larger than the bank and ERP. Error bars ± 1 standard error.

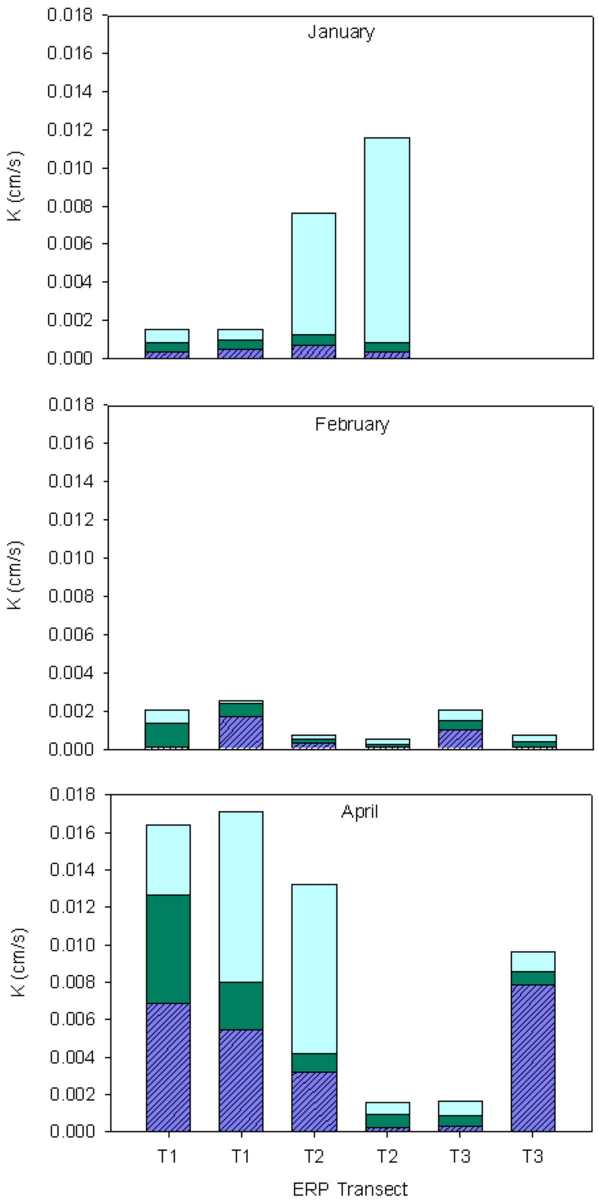


Figure 24 Hydraulic conductivity (K) measured at three transects along the 300m ERP channel at 10cm deep, 15cm, and 20cm during 2011. January data were collected after construction of the ERP, February represents one month of undisturbed development, and April measurements were conducted after drying, ripping, and rewetting the channel.

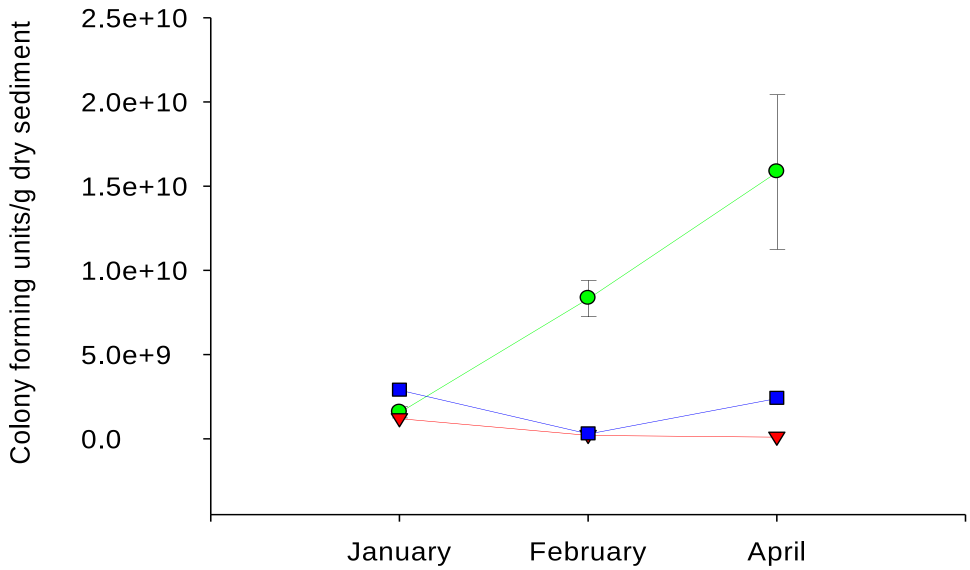


Figure 25 Heterotrophic plate counts of colony forming units of sediment bacteria from the ERP channel , SCR bank , and SCR thalweg during 2011. ERP is averaged from six 20cm sediment cores spanning the three transects, while one core was taken for each SCR site. Error bars ± 1 standard error.

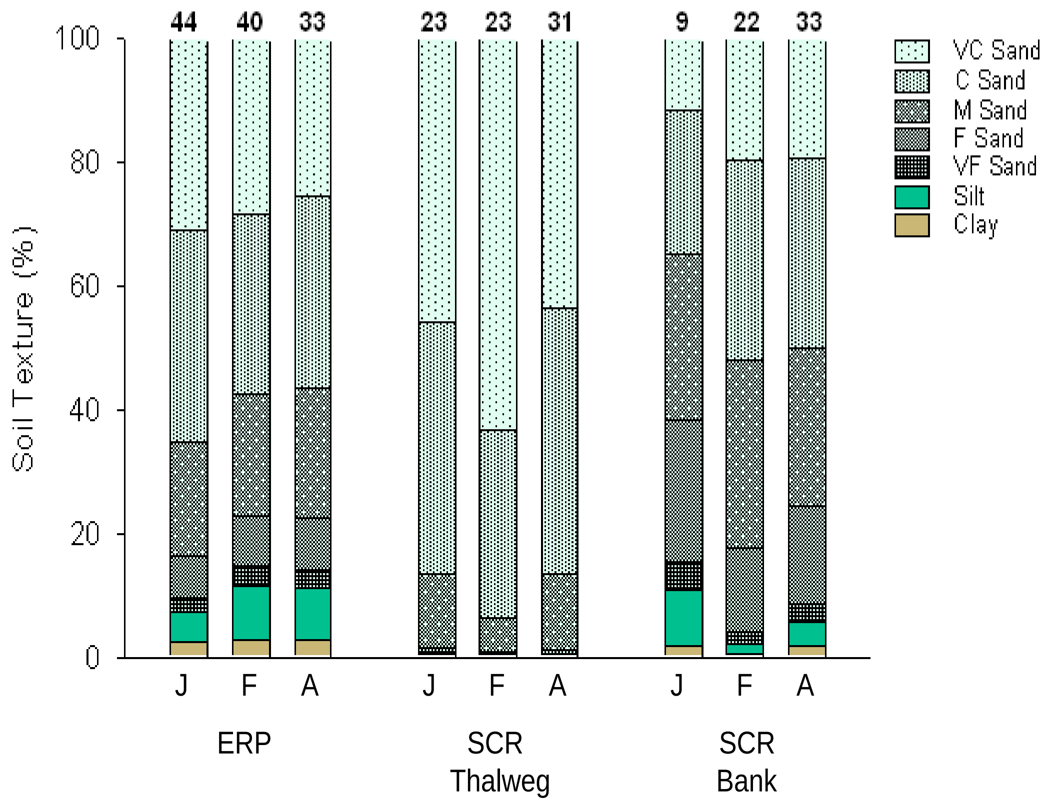


Figure 26 Sediment texture composition from the three sites during January (J), February (F), and April (A) of 2011. Numbers above each bar represent percent gravel of the sample.

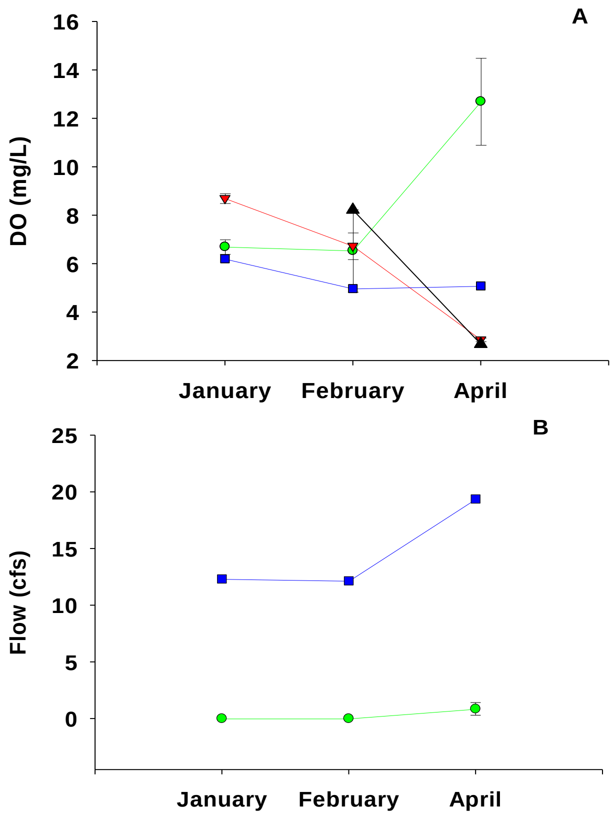


Figure 27 Dissolved oxygen (A) and stream flow (B) of the ERP surface water, ERP pore water, SCR surface water, and SCR bank pore water during 2011. Error bars ± 1 standard error.

Table 3 Pearson's Correlation results for conductivity, bacteria counts, and fine texture sediments during the study.

	r value	p value	Sample size
Conductivity vs Bacteria			
January	-0.103	0.900	4
February	-0.565	0.327	5
April	-0.596	0.215	6
Conductivity vs %Fines			
January	-0.091	0.911	4
February	-0.436	0.467	5
April	-0.542	0.270	6

Table 4 Physical and chemical parameters of surface and sediment porewater for the ERP channel and the Santa Cruz River during 2011.

Date	Site	Location	Temp (C)	DO (mg/L)	pH	ORP (mV)	Flow (cfs)	NH4 (mg/L)	NO3 (mg/L)	TN (mg/L)	NPOC (mg/L)	PO4 (mg/L)
1/29	ERP	surface	18.5	6.7		151	0.00	21.80	6.77	33.23	11.77	
1/29	ERP	sediment	17.7	8.7		147		20.75	6.69	33.79	17.53	
1/29	SCR	surface	17.3	6.2		155	0.35	19.90	5.95	32.97	11.69	
2/26	ERP	surface	14.9	6.5		142	0.00			32.02	13.83	3.26
2/26	ERP	sediment	13.3	6.7		142				30.70	13.89	2.73
2/26	SCR	surface	13.4	5.0		144	0.34			31.57	12.08	3.31
2/26	SCR	sediment, T	13.3	6.3		162				32.46	20.89	3.00
2/26	SCR	sediment, B	13.2	8.2		139				29.98	12.77	3.11
4/16	ERP	surface	29.7	12.7	8.51	278	0.02	12.13	4.54		10.50	2.48
4/16	ERP	sediment	28.4	2.9	7.48	277		15.13	4.47		8.53	2.90
4/16	SCR	surface	28.6	5.1	7.89	256	0.55	13.00	5.21		9.77	2.59
4/16	SCR	sediment, T	27.4	3.0	7.61	95		15.00	1.59		6.42	3.12
4/16	SCR	sediment, B	25.6	2.7	7.51	-92		16.00	0.10		7.14	4.02

*Thalweg sediments
**Bank sediments

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APPENDIX A

HETEROTROPHIC PLATE COUNTS

CFUs/g wet sediment (excess water centrifuged off)

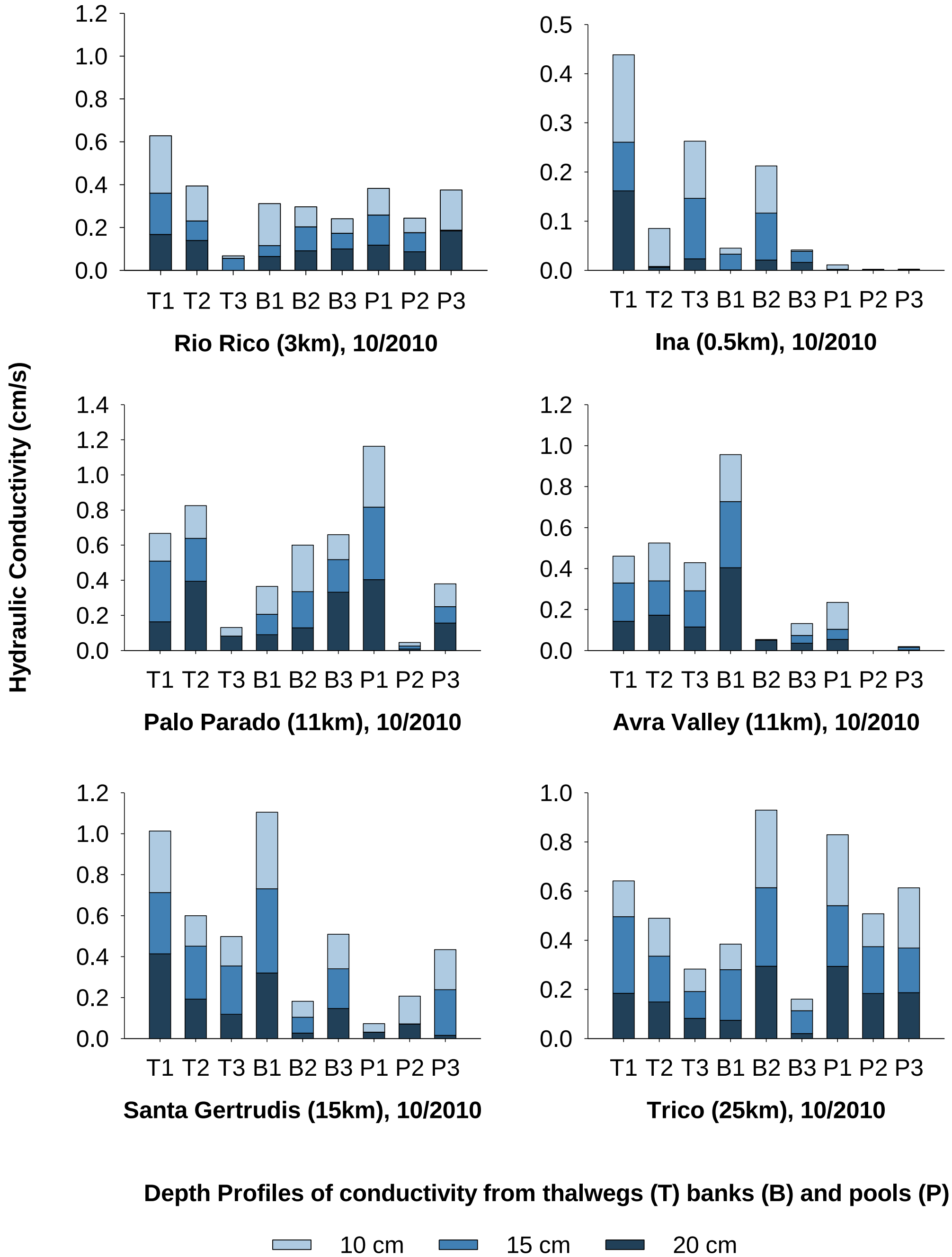
	Santa Cruz River B class reach			Santa Cruz River A+ class reach			San Pedro River		
August 2010	0.5 km	11 km	25 km	3 km	11 km	15 km	Charleston	Lewis Springs	Fairbank
Thalweg	1.6E+08		1.4E+08	3.7E+08		8.7E+07	3.7E+08		1.6E+09
Bank	8.6E+08		7.9E+08			1.7E+08			2.0E+09
Pool	2.8E+08		3.9E+08	7.4E+07		3.5E+08			5.1E+08
October 2010									
Thalweg	4.6E+08	6.7E+07	4.8E+07	5.6E+07	8.6E+07	9.2E+07	6.9E+07		1.0E+08
Bank				3.0E+07					
Pool	3.6E+09	1.5E+09	1.3E+08	4.1E+07	7.8E+08	1.7E+08	5.3E+07		5.8E+08
November 2010									
Thalweg	1.2E+09	6.7E+07	1.3E+07	4.4E+07	3.5E+07	9.0E+07	1.5E+08		1.4E+08
Bank			1.8E+08						
Pool	1.4E+09	1.1E+09	1.6E+09	1.4E+08	2.0E+09	2.5E+08	5.2E+08	6.6E+08	
May 2011									
Thalweg	2.9E+08	6.2E+08	3.7E+07	7.2E+08	1.8E+08	3.7E+08	1.6E+08	2.7E+08	1.6E+08
Bank									
Pool	3.5E+09	1.1E+09	5.0E+07	7.9E+09	4.4E+08	3.6E+08	1.1E+09	1.4E+09	7.7E+08
Average	**1.3E+09**	**7.4E+08**	**3.4E+08**	**1.0E+09**	**5.9E+08**	**2.1E+08**	**3.5E+08**	**7.6E+08**	**7.4E+08**

CFUs/g dry sediment

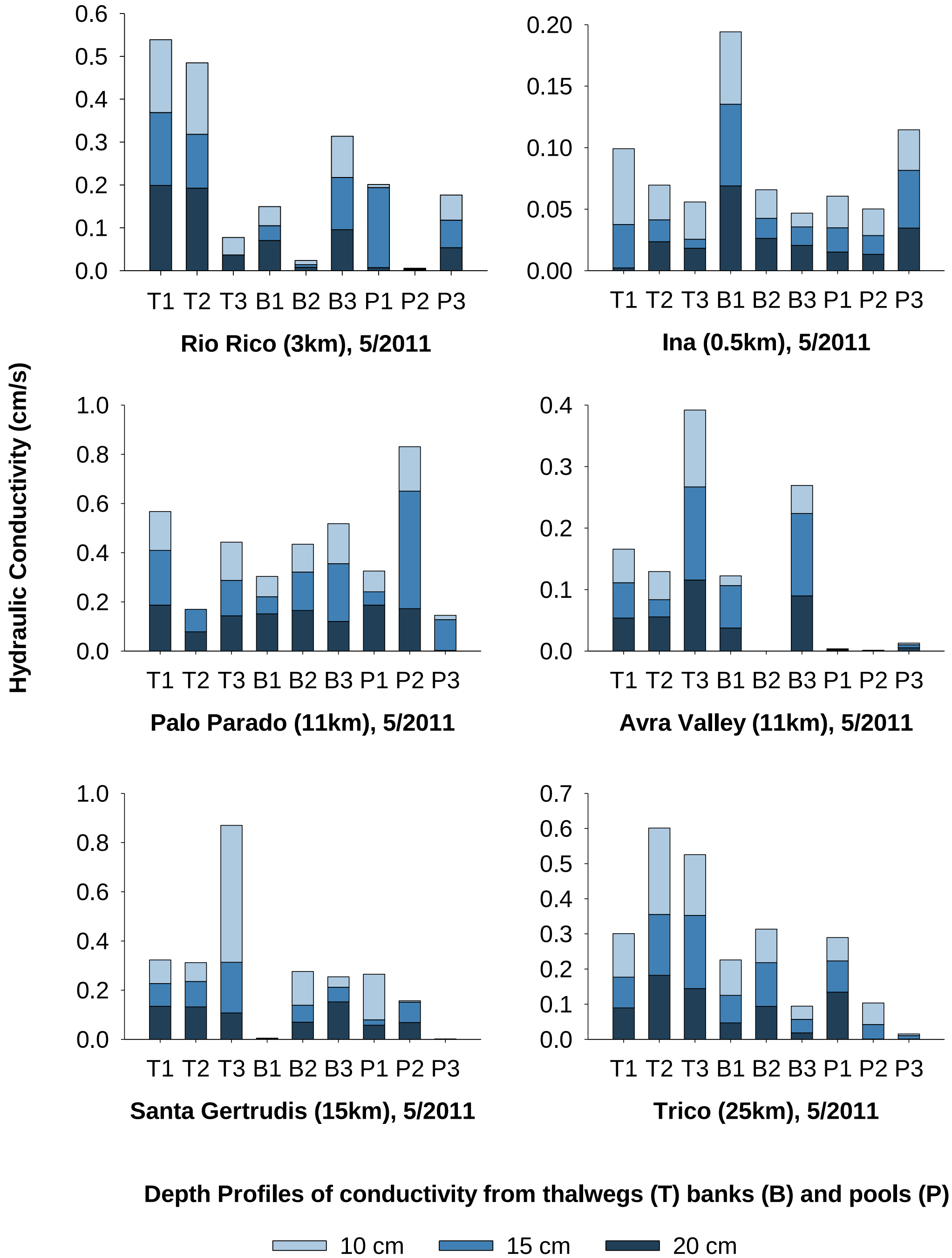
	Santa Cruz River B class reach			Santa Cruz River A+ class reach			San Pedro River		
August 2010	0.5 km	11 km	25 km	3 km	11 km	15 km	Charleston	Lewis Springs	Fairbank
Thalweg	2.0E+08		1.8E+08	4.6E+08		9.8E+07	4.4E+08		2.0E+09
Bank	1.0E+09		1.0E+09			2.2E+08			2.6E+09
Pool	3.4E+08		4.7E+08	9.4E+07		4.0E+08			6.1E+08
October 2010									
Thalweg	5.6E+08	8.0E+07	6.0E+07	6.7E+07	1.1E+08	1.2E+08	8.3E+07		1.2E+08
Bank				3.6E+07					
Pool	4.4E+09	1.9E+09	1.6E+08	5.0E+07	9.3E+08	2.1E+08	6.4E+07		6.8E+08
May 2011									
Thalweg	3.3E+08	7.3E+08	4.4E+07	8.3E+08	2.1E+08	4.3E+08	1.9E+08	3.1E+08	1.9E+08
Bank									
Pool	4.2E+09	1.3E+09	5.9E+07		5.1E+08	4.3E+08	1.2E+09	1.6E+09	9.1E+08

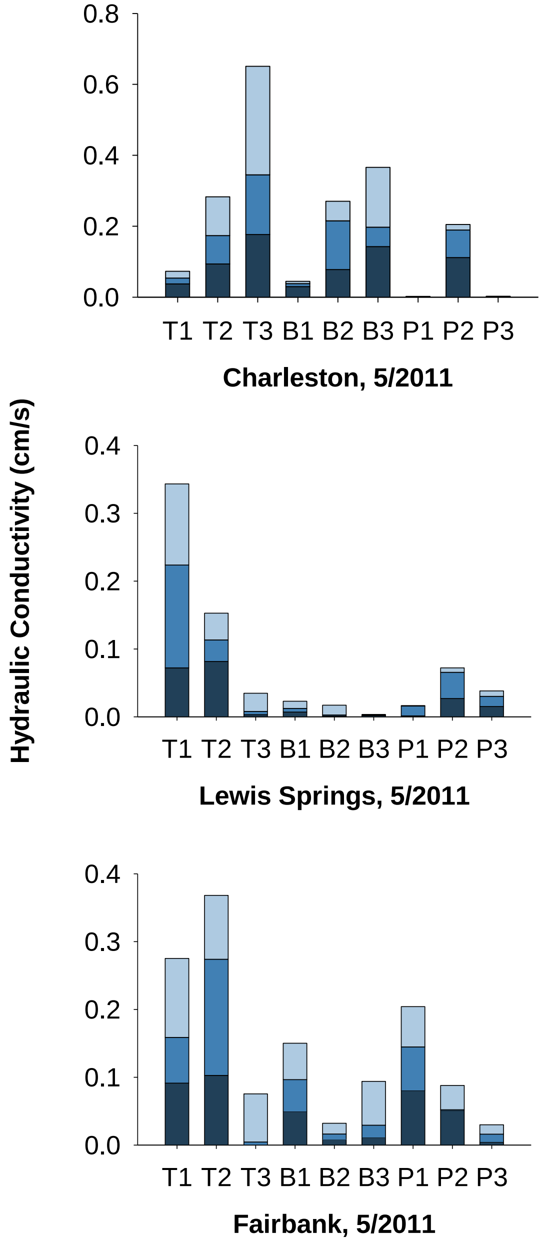
APPENDIX B

HYDRAULIC CONDUCTIVITY OF SEDIMENTS AT DEPTHS OF 10, 15, AND 20CM DURING OCTOBER 2010 AND MAY 2011



Depth Profiles of conductivity from thalwegs (T) banks (B) and pools (P)


Hydraulic Conductivity (cm/s)
0.6
0.5
0.4
0.3
0.2
0.1
0.0
T1 T2 T3 B1 B2 B3 P1 P2 P3
Rio Rico (3km), 5/2011
0.20
0.15
0.10
0.05
0.00
T1 T2 T3 B1 B2 B3 P1 P2 P3
Ina (0.5km), 5/2011
1.0
0.8
0.6
0.4
0.2
0.0
T1 T2 T3 B1 B2 B3 P1 P2 P3
Palo Parado (11km), 5/2011
0.4
0.3
0.2
0.1
0.0
T1 T2 T3 B1 B2 B3 P1 P2 P3
Avra Valley (11km), 5/2011
1.0
0.8
0.6
0.4
0.2
0.0
T1 T2 T3 B1 B2 B3 P1 P2 P3
Santa Gertrudis (15km), 5/2011
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
T1 T2 T3 B1 B2 B3 P1 P2 P3
Trico (25km), 5/2011
Depth Profiles of conductivity from thalwegs (T) banks (B) and pools (P)
10 cm
15 cm
20 cm



Depth Profiles of conductivity from thalwegs (T) banks (B) and pools (P)

10 cm 15 cm 20 cm

APPENDIX C

HYDRAULIC CONDUCTIVITY

Hydraulic conductivity (cm/s), April 2010, sorted smallest to largest

Locations = T(thalweg), B(bank), P(pool); Transects = T 1, 2, 3; Depth of piezometer in cm = D 10, 15, 20.

Lower Santa Cruz B class reach

L/T	D	0.5 km	L/T	D	28 km	L/T	D	38 km
P1	10	0.0004	P1	15	0.0006	B1	10	0.0005
P3	10	0.0004	P2	10	0.0008	P1	10	0.0006
P3	15	0.0005	T2	15	0.0010	P2	10	0.0008
P1	15	0.0007	P2	15	0.0036	B1	15	0.0008
P3	20	0.0008	T2	10	0.0042	P3	15	0.0009
B2	20	0.0010	P1	10	0.0063	P1	15	0.0011
B1	10	0.0013	P2	20	0.0079	P2	15	0.0014
B2	10	0.0014	P1	20	0.0087	B1	20	0.0016
B1	15	0.0015	T2	20	0.0139	P1	20	0.0017
B3	15	0.0021	B2	20	0.1072	P3	20	0.0018
P1	20	0.0022	B2	10	0.1093	P2	20	0.0029
B1	20	0.0045	B1	15	0.1127	P3	10	0.0144
B3	20	0.0048	B1	10	0.1179	T1	15	0.0173
B3	10	0.0080	B2	15	0.1250	T1	10	0.0225
P2	10	0.0196	B1	20	0.1409	T3	15	0.0786
P2	20	0.0286	T1	10	0.1446	T3	10	0.1583
B2	15	0.0347	T1	20	0.1695			
T3	10	0.0390	T1	15	0.1867			
P2	15	0.0488						
T1	10	0.0782						
T3	20	0.0878						
T3	15	0.1009						
T1	20	0.1059						
T1	15	0.1138						
T2	15	0.2103						
T2	20	0.2196						
T2	10	0.2333						

Upper Santa Cruz A+ class reach

L/T	D	3 km	L/T	D	15 km	L/T	D	20 km
P2	10	0.0028	P3	15	0.0063	P2	10	0.0005
P2	15	0.0198	P3	10	0.0119	P2	15	0.0010
P1	10	0.0337	P1	15	0.0180	P3	20	0.0038
P2	20	0.0359	P1	20	0.0252	P2	20	0.0065
P1	15	0.0439	P1	10	0.0450	B1	20	0.0160
P1	20	0.0698	P3	20	0.0460	P3	15	0.0184
T2	15	0.1111	T1	20	0.1461	P3	10	0.0283
B1	15	0.1122	T3	10	0.1539	B1	10	0.0423
B2	15	0.1128	T1	15	0.1800	B3	20	0.0445
B2	10	0.1159	B3	10	0.1829	T3	20	0.0992
B2	20	0.1397	T1	10	0.1831	T3	10	0.1012
T2	20	0.1527	T3	15	0.1862	B1	15	0.1067
B1	20	0.1613	B3	20	0.2162	B2	10	0.1126
T1	15	0.1716	B1	15	0.2226	T3	15	0.1380
T1	10	0.1925	B1	20	0.2246	T1	20	0.1697
T1	20	0.2132	B3	15	0.2354	B2	15	0.1991
T2	10	0.3176	B1	10	0.2539	B3	15	0.2089
			T3	20	0.2826	B2	20	0.2154
						T2	10	0.2192
						B3	10	0.2303
						T1	10	0.2333
						P1	15	0.2878
						T1	15	0.2988
						P1	20	0.3572
						T2	20	0.3654
						T2	15	0.3714
						P1	10	0.4089

San Pedro River

L/T	D	Lewis Springs	L/T	D	Fairbank
P1	10	0.0003	P2	20	0.0009
B2	10	0.0004	P2	15	0.0029
B1	10	0.0004	P3	15	0.0029
P2	15	0.0004	P3	20	0.0036
P1	15	0.0005	P3	10	0.0053
B1	15	0.0006	P2	10	0.0065
B2	15	0.0006	T2	10	0.0236
B2	20	0.0009	T3	15	0.0260
B1	20	0.0010	B2	10	0.0269
P2	20	0.0018	T3	10	0.0398
P2	10	0.0023	B3	15	0.0404
P3	10	0.0026	T2	15	0.0468
B3	20	0.0030	B3	10	0.0494
P3	15	0.0049	T3	20	0.0494
B3	10	0.0061	B3	20	0.0537
B3	15	0.0084	T2	20	0.0637
P3	20	0.0130	B2	15	0.0916
P1	20	0.0222	B2	20	0.1176
T3	10	0.0304			
T3	20	0.0350			
T1	15	0.0390			
T1	10	0.0390			
T2	20	0.0546			
T2	10	0.0563			
T1	20	0.0642			
T3	15	0.0757			
T2	15	0.1591			

Hydraulic conductivity (cm/s), August 2010, sorted smallest to largest

Locations = T(thalweg), B(bank), P(pool); Transects = T 1, 2, 3; Depth of piezometer in cm

Lower Santa Cruz B class reach						Upper Santa Cruz A+ class reach								
L/T	D	0.5 km	L/T	D	25 km	L/T	D	3 km	L/T	D	15 km	L/T	D	20 km
B2	10	0.0003	B3	20	0.0010	T1	20	0.0027	P1	20	0.0007	B3	10	0.0007
B2	15	0.0005	B3	10	0.0646	T3	10	0.0101	B3	15	0.0062	P3	10	0.0011
P2	15	0.0006	P3	15	0.0654	B1	20	0.0149	P1	10	0.0230	P3	15	0.0013
P2	20	0.0007	T1	10	0.0718	P2	10	0.0173	P3	15	0.0459	P3	20	0.0124
B2	20	0.0008	T1	20	0.0869	P1	10	0.0275	B3	10	0.0570	T3	10	0.0479
P2	10	0.0024	B3	15	0.0924	B3	20	0.0324	B3	20	0.0972	T3	15	0.0658
P1	20	0.0177	T1	15	0.0980	P2	20	0.0470	B2	20	0.1143	T3	20	0.0750
P1	10	0.0244	B2	10	0.1064	P3	10	0.0487	P3	10	0.1199	B3	15	0.0802
B1	20	0.0323	T3	15	0.1208	P2	15	0.0526	P1	15	0.1223	B2	15	0.1635
B1	15	0.0336	P1	20	0.1247	P1	15	0.0554	P3	20	0.1452	B3	20	0.2298
T1	20	0.0341	P1	10	0.1289	B1	10	0.0599	P2	15	0.1551	B1	10	0.2330
P3	10	0.0419	P3	20	0.1390	B1	15	0.0606	B1	15	0.1556	B2	20	0.2436
P1	15	0.0492	B1	20	0.1395	T3	15	0.0627	P2	20	0.1571	B1	15	0.2444
T1	10	0.0530	P3	10	0.1397	T1	15	0.0769	T3	20	0.1919	T2	15	0.2604
T1	15	0.0560	B2	15	0.1438	B2	15	0.0774	B1	10	0.2134	P1	20	0.2773
T3	20	0.0621	T2	20	0.1442	B2	10	0.1175	B2	15	0.2188	P1	15	0.3163
P3	15	0.0735	T2	10	0.1663	T3	20	0.1179	B2	10	0.2330	T2	10	0.3223
T3	10	0.0889	P1	15	0.1715	B2	20	0.1315	T3	10	0.2340	B1	20	0.3236
B1	10	0.0900	T2	15	0.1769	T1	10	0.1431	T3	15	0.2853	T2	20	0.3385
P3	20	0.1129	B2	20	0.1796	P3	15	0.1541	P2	10	0.2925	T1	20	0.3438
T3	15	0.1260	T3	10	0.1942	T2	15	0.1598	B1	20	0.3328	P2	10	0.3516
B3	15	0.1952	T3	20	0.2143	P3	20	0.1939	T1	20	0.3944	T1	10	0.3826
B3	20	0.1984	P2	15	0.2178	T2	10	0.1962	T1	15	0.4232	P2	20	0.4038
B3	10	0.2032	B1	10	0.2296	P1	20	0.2028	T1	10	0.4380	B2	10	0.4364
T2	10	0.2053	P2	20	0.2394	B3	10	0.2073	T2	20	0.5999	P2	15	0.4514
T2	15	0.2286	B1	15	0.2397	T2	20	0.2073	T2	15	0.7313	P1	10	0.5967
T2	20	0.3145	P2	10	0.2452	B3	15	0.2246	T2	10	0.7757	T1	15	0.5982

Hydraulic conductivity (cm/s), October 2010, sorted smallest to largest

Locations = T(thalweg), B(bank), P(pool); Transects = T 1, 2, 3; Depth of piezometer in cm = D 10, 15, 20.

Lower Santa Cruz B class reach									Upper Santa Cruz A+ class reach								
L/T	D	0.5 km	L/T	D	11 km	L/T	D	25 km	L/T	D	3 km	L/T	D	11 km	L/T	D	15 km
P2	15	0.0004	P2	10	0.0003	B3	20	0.0200	T3	20	0.0010	P2	20	0.0087	P1	15	0.0004
P1	15	0.0005	P2	15	0.0005	B3	10	0.0471	P3	15	0.0028	P2	15	0.0167	P2	15	0.0005
P3	15	0.0006	P2	20	0.0008	B1	20	0.0744	T3	10	0.0115	P2	10	0.0205	P3	20	0.0158
P2	20	0.0007	B2	15	0.0009	T3	20	0.0822	B1	15	0.0507	T3	10	0.0490	B2	20	0.0270
P3	20	0.0009	P3	20	0.0020	T3	10	0.0914	T3	15	0.0552	T3	20	0.0819	P1	20	0.0311
B1	20	0.0009	B2	10	0.0020	B3	15	0.0933	B1	20	0.0643	B1	20	0.0897	P1	10	0.0413
P3	10	0.0010	P3	10	0.0034	B1	10	0.1037	B3	10	0.0675	P3	15	0.0934	P2	20	0.0713
P2	10	0.0010	P3	15	0.0136	T3	15	0.1093	P2	10	0.0679	B1	15	0.1162	B2	15	0.0771
P1	20	0.0016	B3	20	0.0359	P2	10	0.1337	B3	15	0.0737	B2	20	0.1293	B2	10	0.0781
T2	15	0.0018	B3	15	0.0376	T1	10	0.1455	P2	20	0.0863	P3	10	0.1303	T3	20	0.1183
B3	10	0.0030	P1	15	0.0486	T2	20	0.1489	P2	15	0.0895	B2	10	0.1424	P2	10	0.1357
T2	20	0.0061	B2	20	0.0510	T2	10	0.1540	B2	20	0.0912	P3	20	0.1561	T3	10	0.1441
P1	10	0.0090	P1	20	0.0546	P3	15	0.1811	T2	15	0.0914	T1	10	0.1570	B3	20	0.1465
B1	10	0.0121	B3	10	0.0583	P2	20	0.1833	B2	10	0.0935	B3	10	0.1591	T2	10	0.1490
B3	20	0.0161	T3	20	0.1150	T1	20	0.1842	B3	20	0.0994	T1	20	0.1631	B3	10	0.1684
B2	20	0.0210	T1	10	0.1309	T2	15	0.1864	B2	15	0.1115	B3	15	0.1852	T2	20	0.1924
B3	15	0.0224	P1	10	0.1319	P3	20	0.1870	P1	20	0.1172	T2	10	0.1865	B3	15	0.1940
T3	20	0.0233	T3	10	0.1371	P2	15	0.1907	P1	10	0.1241	B2	15	0.2056	P3	10	0.1957
B1	15	0.0320	T1	20	0.1424	B1	15	0.2059	T2	20	0.1392	T2	15	0.2444	P3	15	0.2228
T2	10	0.0772	T2	15	0.1672	P3	10	0.2449	P1	15	0.1410	B1	10	0.2655	T3	15	0.2357
B2	15	0.0955	T2	20	0.1726	P1	15	0.2471	T2	10	0.1634	B3	20	0.3322	T2	15	0.2585
B2	10	0.0960	T3	15	0.1766	P1	10	0.2887	T1	20	0.1672	T1	15	0.3463	T1	15	0.2988
T1	15	0.099	T2	10	0.1851	P1	20	0.2937	P3	20	0.1846	P1	10	0.3468	T1	10	0.3006
T3	10	0.1163	T1	15	0.1870	B2	20	0.2945	P3	10	0.1878	T2	20	0.3943	B1	20	0.3198
T3	15	0.1230	B1	10	0.2287	T1	15	0.3117	T1	15	0.1927	P1	20	0.4036	B1	10	0.3739
T1	20	0.1617	B1	15	0.3228	B2	10	0.3158	B1	10	0.1965	P1	15	0.4130	B1	15	0.4112
T1	10	0.1777	B1	20	0.4043	B2	15	0.3191	T1	10	0.2680	T3	15		T1	20	0.4136

Hydraulic conductivity (cm/s), November 2010, sorted smallest to largest

Locations = T(thalweg), B(bank), P(pool); Transects = T 1, 2, 3; Depth of piezometer in cm = D 10, 15, 20.

Lower Santa Cruz B class reach									Upper Santa Cruz A+ class reach								
L/T	D	0.5 km	L/T	D	11 km	L/T	D	25 km	L/T	D	3 km	L/T	D	11 km	L/T	D	15 km
P1	15	0.0006	P2	10	0.0003	B3	20	0.0017	B2	10	0.0154	P2	20	0.0052	B3	20	0.0008
P2	20	0.0006	P1	10	0.0003	B3	15	0.0035	B1	15	0.0253	P2	10	0.0493	P2	15	0.0048
P1	20	0.0011	P3	10	0.0004	B1	20	0.0036	B2	20	0.0390	B2	15	0.0559	P2	20	0.0115
B3	20	0.0016	P2	15	0.0004	B1	15	0.0054	P1	20	0.0404	B2	20	0.0565	P3	15	0.0270
P1	10	0.0023	P1	15	0.0005	P1	15	0.0129	P2	20	0.0411	B2	10	0.0575	P3	10	0.0344
B3	10	0.0031	P2	20	0.0007	P1	20	0.0141	B3	20	0.0464	P3	10	0.0723	P3	20	0.0357
B3	15	0.0046	P1	20	0.0007	P1	10	0.0327	B2	15	0.0470	P3	15	0.0780	B3	10	0.0421
P3	20	0.0067	B1	20	0.0010	B1	10	0.0486	P2	10	0.0536	B3	20	0.0793	B3	15	0.0444
B1	10	0.0071	P3	15	0.0010	P3	10	0.0584	P1	10	0.0563	B1	10	0.0804	P2	10	0.0696
T3	20	0.0073	P3	20	0.0017	T2	20	0.0662	P2	15	0.0616	B1	20	0.1143	B1	10	0.0728
B1	20	0.0108	B3	15	0.0372	T3	15	0.0736	B1	20	0.0687	T3	15	0.1174	T2	10	0.0732
T2	10	0.0161	B2	20	0.0385	P2	20	0.0753	T1	20	0.0761	B1	15	0.1226	P1	10	0.0741
B1	15	0.0226	B3	20	0.0502	B2	20	0.0966	P3	10	0.0869	T1	10	0.1336	P1	15	0.0851
P2	10	0.0235	B3	10	0.0522	P3	20	0.1144	T3	10	0.0875	T3	10	0.1502	P1	20	0.0885
P3	10	0.0278	B2	15	0.0748	B2	10	0.1157	B3	15	0.0884	P1	10	0.1543	B2	10	0.1036
P2	15	0.0281	B1	15	0.0940	T2	10	0.1210	T1	15	0.0949	P3	20	0.1644	B2	15	0.1050
T2	20	0.0323	B1	10	0.0961	T2	15	0.1243	B3	10	0.1006	P1	20	0.1884	B2	20	0.1151
B2	15	0.0384	T2	20	0.1177	B2	15	0.1301	T3	15	0.1113	P2	15	0.2057	B1	20	0.1456
T2	15	0.0489	T2	10	0.1329	P2	10	0.1400	P1	15	0.1144	B3	15	0.2132	T3	20	0.1486
B2	20	0.0627	T1	20	0.1519	P3	15	0.1424	T2	10	0.1266	T3	20	0.2212	T2	20	0.1527
P3	15	0.0647	T3	10	0.1631	P2	15	0.1455	P3	15	0.1386	T2	20	0.2336	B1	15	0.1580
B2	10	0.0698	B2	10	0.1770	T3	20	0.1476	T1	10	0.1439	P1	15	0.2436	T2	15	0.1599
T3	15	0.0841	T3	15	0.1789	T3	10	0.1714	B1	10	0.1472	T1	15	0.2680	T3	15	0.1625
T3	10	0.1238	T1	10	0.1868	T1	15	0.1807	P3	20	0.1507	T1	20	0.3174	T1	10	0.1821
T1	20	0.1360	T3	20	0.1882	T1	20	0.1966	T3	20	0.1721	T2	10	0.3570	T1	15	0.1924
T1	15	0.1614	T2	15	0.1949	T1	10	0.2014	T2	15	0.2130	T2	15	0.3892	T1	20	0.2271
T1	10	0.2782	T1	15	0.2107	B3	10	0.2219	T2	20	0.2920				T3	10	0.2843

Hydraulic conductivity (cm/s), May 2011, sorted smallest to largest

Locations = T(thalweg), B(bank), P(pool); Transects = T 1, 2, 3; Depth of piezometer in cm = D 10, 15, 20.

Lower Santa Cruz B class reach

L/T	D	0.5 km	L/T	D	11 km	L/T	D	25 km
T3	20	0.0022	P1	10	0.0003	P3	20	0.0008
T2	15	0.0072	P2	15	0.0004	P3	20	0.0008
B1	10	0.0111	P3	20	0.0006	P1	10	0.0045
P3	20	0.0133	P3	20	0.0010	P2	15	0.0098
B2	15	0.0150	P2	15	0.0013	B3	20	0.0182
P3	20	0.0151	P1	10	0.0015	B1	10	0.0377
P2	15	0.0153	P1	10	0.0029	B2	15	0.0385
B2	15	0.0163	P2	15	0.0049	P2	15	0.0416
T2	15	0.0179	P3	20	0.0052	B3	20	0.0468
T3	20	0.0183	B1	10	0.0158	P1	10	0.0610
P2	15	0.0197	T2	15	0.0280	P1	10	0.0666
B3	20	0.0206	B3	20	0.0375	B2	15	0.0783
P1	10	0.0215	B1	10	0.0456	T2	15	0.0878
B1	10	0.0232	T1	10	0.0459	P2	15	0.0887
T3	20	0.0235	T3	20	0.0537	T3	20	0.0893
P1	10	0.0257	T1	10	0.0547	B3	20	0.0936
B3	20	0.0263	T3	20	0.0555	B1	10	0.0954
T1	10	0.0282	T2	15	0.0573	B1	10	0.1007
T1	10	0.0304	B2	15	0.0689	T1	10	0.1237
P1	10	0.0330	B3	20	0.0896	B2	15	0.1245
P3	20	0.0347	T3	20	0.1155	P3	20	0.1342
T2	15	0.0354	T1	10	0.1250	T3	20	0.1444
P2	15	0.0468	B2	15	0.1341	T1	10	0.1730
B1	10	0.0588	T2	15	0.1514	T2	15	0.1733
T1	10	0.0616				T3	20	0.1822
B2	15	0.0664				T2	15	0.2082
B3	20	0.0689				T1	10	0.2456

Upper Santa Cruz A+ class reach

L/T	D	3 km	L/T	D	11 km	L/T	D	15 km
P2	15	0.0010	P3	20	0.0023	P3	10	0.0004
P2	10	0.0020	P3	10	0.0173	P3	15	0.0005
P2	20	0.0026	P1	15	0.0538	B1	20	0.0007
B2	15	0.0063	B1	15	0.0696	P3	20	0.0008
P1	20	0.0070	T2	20	0.0780	B1	10	0.0012
P1	10	0.0071	B1	10	0.0827	B1	15	0.0028
B2	20	0.0077	P1	10	0.0843	P2	10	0.0057
B2	10	0.0096	T2	15	0.0918	P1	15	0.0218
B1	15	0.0350	B2	10	0.1128	B3	10	0.0428
T3	20	0.0365	B3	20	0.1201	P1	20	0.0574
T3	10	0.0408	P3	15	0.1255	B3	15	0.0596
B1	10	0.0445	T3	20	0.1435	P2	20	0.0681
P3	20	0.0536	T3	15	0.1436	B2	15	0.0691
P3	10	0.0585	B1	20	0.1511	B2	20	0.0696
P3	15	0.0641	T3	10	0.1556	T2	10	0.0768
B1	20	0.0700	B2	15	0.1567	P2	15	0.0830
B3	20	0.0954	T1	10	0.1578	T1	15	0.0922
B3	10	0.0960	B3	10	0.1623	T1	10	0.0959
B3	15	0.1220	B2	20	0.1646	T2	15	0.1030
T2	15	0.1257	P2	20	0.1720	T3	20	0.1072
T2	10	0.1667	P2	10	0.1808	T2	20	0.1320
T1	10	0.1699	T1	20	0.1870	T1	20	0.1345
T1	15	0.1702	P1	20	0.1870	B2	10	0.1373
P1	15	0.1868	T1	15	0.2225	B3	20	0.1520
T2	20	0.1925	B3	15	0.2353	P1	10	0.1856
T1	20	0.1987	P2	15	0.4781	T3	15	0.2060
						T3	10	0.5565

San Pedro River

L/T	D	Charleston	L/T	D	Lewis Springs	L/T	D	Fairbank
P1	10	0.0003	B1	10	0.0004	P2	15	0.0009
P2	15	0.0006	P1	10	0.0007	P3	20	0.0042
P2	15	0.0006	B3	20	0.0009	T2	15	0.0046
P3	20	0.0009	B2	15	0.0011	B2	15	0.0076
P1	10	0.0011	P3	20	0.0012	B3	20	0.0087
P3	20	0.0011	B3	20	0.0017	B3	20	0.0113
B1	10	0.0062	B2	15	0.0019	P2	15	0.0119
B2	15	0.0087	T3	20	0.0030	P1	10	0.0138
P1	10	0.0156	T2	15	0.0048	B1	10	0.0159
T2	15	0.0165	B2	15	0.0055	B2	15	0.0181
T1	10	0.0190	P1	10	0.0065	P1	10	0.0359
B3	20	0.0296	B3	20	0.0069	B2	15	0.0470
T3	20	0.0373	P1	10	0.0080	B3	20	0.0495
B2	15	0.0548	B1	10	0.0105	P3	20	0.0511
B1	10	0.0553	B1	10	0.0144	B1	10	0.0535
B3	20	0.0780	P2	15	0.0146	P1	10	0.0595
P2	15	0.0780	P2	15	0.0149	P2	15	0.0644
T2	15	0.0797	P3	20	0.0152	B1	10	0.0646
T3	20	0.0937	T1	10	0.0268	T2	15	0.0674
T1	10	0.1096	P3	20	0.0269	T1	10	0.0709
P3	20	0.1113	T2	15	0.0319	P3	20	0.0803
B2	15	0.1371	P2	15	0.0386	T3	20	0.0913
B3	20	0.1425	T1	10	0.0393	T1	10	0.0942
T2	15	0.1680	T3	20	0.0721	T3	20	0.1026
B1	10	0.1688	T3	20	0.0815	T1	10	0.1165
T3	20	0.1768	T1	10	0.1195	T2	15	0.1713
T1	10	0.3064	T2	15	0.1517			

APPENDIX D

SEDIMENT TEXTURE ANALYSIS

Percent sediment texture, April 2010, from Thalwegs (T), Banks (B), and Pools (P) spanning a 200m reach

(Clay < 2 µm, Silt 2-63 µm, Very Fine Sand 63-125 µm, Fine Sand 125-250 µm, Medium Sand 250-500 µm, Coarse Sand 500-1000 µm, Very Coarse Sand 1-2 mm, Gravel 2-40 mm)

Lower Santa Cruz, B class reach

	Clay	Silt	VF Sand	F Sand	M Sand	C Sand	VC Sand	Gravel
				0.5km				
T1	0.67	1.12	0.16	5.06	22.45	38.19	32.33	46.96
T2	0.67	0.72	0.06	2.30	23.99	39.02	33.15	53.17
T3	0.67	1.01	0.12	5.43	23.77	29.58	39.49	61.68
B1	2.75	8.03	34.89	28.60	5.44	8.80	11.03	31.36
B2	0.00	2.43	0.94	8.91	27.57	36.70	23.50	21.74
B3	2.00	0.81	3.69	12.53	40.73	26.71	13.58	47.41
P1	4.66	27.73	26.48	23.96	11.20	3.87	1.93	3.17
P2	0.67	2.08	2.27	16.34	23.82	34.63	20.18	7.98
P3	1.33	4.01	8.84	22.41	28.72	24.72	9.95	19.32
				28km				
T1	0.00	8.93	0.07	2.09	20.88	34.23	33.60	18.58
T2	0.67	2.75	0.03	1.38	28.87	41.66	24.59	4.91
B1	2.66	11.03	0.41	2.76	24.49	37.28	21.24	4.36
B2	0.00	1.72	0.03	1.04	25.08	41.51	30.48	3.73
P1	0.00	14.84	0.67	3.79	23.38	33.29	23.85	11.56
P2	0.00	3.05	0.11	1.84	38.71	43.64	12.66	3.28
				38km				
T1	1.33	3.31	1.10	6.94	28.55	41.23	17.46	7.03
T2	0.67	1.97	0.12	0.84	20.31	55.30	20.74	3.62
T3	1.32	2.32	0.69	1.32	18.03	52.04	24.17	7.76
B1	2.66	3.21	8.49	13.81	31.91	29.25	10.73	2.95
B2	13.31	56.18	19.80	8.75	1.44	0.41	0.12	2.51
B3								
P1	12.68	32.87	19.09	28.51	4.20	2.23	0.46	2.65
P2	10.00	27.25	5.46	8.50	26.42	19.12	3.27	9.14
P3	2.67	9.79	4.10	7.22	31.64	31.08	13.34	7.65

Upper Santa Cruz, A+ class reach

	Clay	Silt	VF Sand	F Sand	M Sand	C Sand	VC Sand	Gravel
				3km				
T1	1.33	5.27	0.10	2.10	23.41	37.16	30.49	38.97
T2	2.00	0.07	0.45	5.81	31.50	31.18	28.90	57.27
B1	1.33	1.40	0.22	1.49	12.34	42.69	40.50	24.94
B2	1.33	0.07	0.11	2.59	27.38	44.86	23.53	15.95
P1	2.66	0.05	1.37	8.13	36.08	36.42	15.13	5.61
P2	2.00	0.04	4.56	8.66	11.53	27.40	46.31	85.77
				15km				
T1	2.66	0.84	0.18	1.19	12.24	34.20	48.65	50.88
T3	1.33	1.04	0.02	0.24	7.14	36.75	53.57	32.05
B1	0.67	0.63	0.02	0.17	18.01	58.30	22.16	4.23
B3	1.99	1.47	0.36	1.76	10.70	30.90	52.75	64.20
P1	3.33	3.40	4.40	12.34	17.71	22.69	36.05	42.93
P3	1.98	1.89	2.56	3.19	8.28	33.20	48.91	48.92
				20km				
T1	0.67	1.31	0.12	1.13	11.46	35.42	49.73	53.77
T2								
T3	1.33	1.51	0.09	0.66	13.37	49.89	33.20	22.26
B1	0.67	1.72	0.03	0.51	12.25	43.66	41.18	31.74
B2	0.67	0.79	0.08	0.19	3.90	46.63	47.73	11.98
B3	0.00	1.92	0.03	0.15	12.95	55.34	29.60	8.08
P1	0.00	2.73	0.38	1.07	3.97	18.57	73.80	83.22
P2	2.00	4.05	3.68	10.37	13.07	37.68	29.08	8.18
P3	2.66	7.59	0.29	1.25	17.15	53.02	17.90	14.34

San Pedro River

	Clay	Silt	VF Sand	F Sand	M Sand	C Sand	VC Sand	Gravel
				Charleston				
				Lewis Springs				
T1	2.00	0.81	0.17	0.36	10.60	48.24	37.81	20.87
T2	2.26	1.20	0.44	2.70	7.23	39.61	46.53	56.50
T3	2.67	0.83	0.56	3.13	34.27	40.82	17.80	14.17
B1	4.67	7.77	7.97	17.29	23.75	22.67	15.93	14.13
B2								
B3	7.32	10.15	15.99	35.25	19.30	7.07	4.88	18.76
P1	2.34	2.25	1.27	2.10	8.31	38.77	44.97	51.60
P2	7.34	9.77	1.32	2.87	10.82	35.84	31.96	48.45
P3	2.00	2.10	0.51	1.24	5.25	26.76	62.18	59.93
				Fairbank				
T2	3.33	0.81	0.88	4.56	12.42	31.65	51.84	66.35
T3	2.67	1.99	0.11	1.25	12.85	44.57	36.56	18.24
B2	2.00	1.84	0.17	1.55	12.71	35.22	46.39	24.00
B3	4.65	1.31	0.10	0.89	7.52	35.73	49.76	28.17
P2	4.64	3.68	0.46	3.55	15.71	30.07	41.86	29.33
P3	2.00	2.12	0.21	1.60	15.82	50.26	27.97	3.61

Percent sediment texture, August 2010, from Thalwegs (T), Banks (B), and Pools (P) spanning a 200m reach

(Clay < 2 µm, Silt 2-63 µm, Very Fine Sand 63-125 µm, Fine Sand 125-250 µm, Medium Sand 250-500 µm, Coarse Sand 500-1000 µm, Very Coarse Sand 1-2 mm, Gravel 2-40 mm)

Lower Santa Cruz, B class reach

	Clay	Silt	VF Sand	F Sand	M Sand	C Sand	VC Sand	Gravel
0.5km								
T1	1.33	1.17	1.8	4.9	14.1	32.9	44.0 ?	
T2	0.67	0.76	0.6	1.9	14.1	38.5	43.4 ?	
T3	2.00	4.13	1.3	8.1	25.0	36.1	23.3	11.49
B1	1.33	2.16	0.9	2.1	10.5	34.5	48.6 ?	
B2	4.66	19.38	20.1	20.1	7.9	9.8	7.3	16.44
B3	0.67	0.87	0.1	1.6	25.0	47.0	24.7	11.355
P1	2.00	1.03	2.1	5.2	19.3	41.9	28.4 ?	
P2	3.32	19.46	18.6	7.2	8.3	25.2	13.3 ?	
P3	1.33	0.84	0.6	4.4	27.4	36.3	29.1	40.60
15km								
25km								
T1	0.67	0.79	0.2	3.5	43.6	36.2	14.9	3.52
T2	0.67	1.08	0.4	4.7	19.3	31.0	42.9	
T3	0.67	1.08	0.2	2.8	18.7	41.3	35.3	
B1	6.01	6.74	4.0	14.2	41.1	20.5	6.6	7.04
B2	0.67	1.03	0.8	2.5	7.6	37.0	50.3	
B3	2.00	0.00	1.0	2.4	9.5	35.3	49.9	
P1	1.33	1.01	0.5	2.9	18.4	29.7	46.1	32.36
P2	2.00	0.00	0.6	1.6	6.5	31.0	58.2	
P3	2.00	0.00	0.3	1.9	12.1	46.6	37.2	

Upper Santa Cruz, A+ class reach

	Clay	Silt	VF Sand	F Sand	M Sand	C Sand	VC Sand	Gravel
3km								
T1	2.00	2.43	2.7	9.1	13.6	28.2	42.1	69.07
T2	0.00	1.85	0.5	3.8	21.8	37.5	34.8	49.62
T3	0	8.138	1.7	10.7	37.0	26.5	15.9	56.08
B1	1.00	0.00	8.1	13.2	15.6	24.4	36.5	42.50
B2	1.33	0.87	0.4	5.1	18.3	37.3	36.9	9.85
B3	0.00	4.50	2.1	3.1	8.6	29.1	54.0	75.62
P1	0.67	1.00	0.9	1.8	5.8	30.2	59.7	53.28
P2	2.00	1.64	1.6	2.6	6.0	31.9	54.6	83.64
P3	0.67	3.69	0.4	3.6	18.6	36.2	42.5	54.69
15km								
T1	1.33	7.50	0.1	0.2	5.5	53.8	45.0	17.67
T2	0.00	2.11	0.4	2.8	19.5	40.7	35.7	78.89
T3	0.00	1.59	0.3	2.1	13.9	37.6	44.6	34.54
B1	2.00	8.83	0.3	0.8	9.2	49.0	43.7	33.64
B2	0.67	0.84	2.4	5.2	18.2	50.5	22.3	22.97
B3	0.00	0.76	0.1	0.2	6.7	48.4	44.0	14.72
P1	2.00	1.64	1.6	3.4	10.5	34.8	46.1	44.06
P2	0.67	1.29	0.6	3.6	20.9	38.9	33.9	34.87
P3	2.02	1.68	0.7	3.1	19.1	38.1	35.3	
20km								
T1	2.00	1.09	0.3	9.2	8.4	41.0	46.5	28.28
T2	2.00	0.43	0.2	1.2	11.3	46.1	38.8	15.53
T3	2.00	1.34	0.6	9.1	17.5	24.5	45.1	44.56
B1	2.00	0.19	0.2	1.6	12.5	37.0	51.8	48.49
B2	1.33	2.21	0.1	0.4	5.5	40.1	50.6	37.43
B3	1.33	1.68	0.2	1.8	8.0	44.5	42.7	11.91
P1	1.33	1.48	0.2	0.4	3.5	31.6	61.8	33.44
P2	1.33	1.07	0.1	0.2	3.0	41.2	53.3	22.73
P3	2.00	1.68	0.3	1.0	5.1	32.7	57.7	6.51

San Pedro River

	Clay	Silt	VF Sand	F Sand	M Sand	C Sand	VC Sand	Gravel
Charleston								
Lewis Springs								
Fairbank								
T1	2.00	0.64	0.4	9.6	27.7	30.2	29.3	
T2	2.67	6.98	0.2	0.5	5.1	33.8	64.6	32.60
T3	3.33	2.85	1.8	10.3	23.1	26.5	32.1	27.25
B1	8.67	14.80	2.2	2.1	7.2	37.4	27.5	12.65
B2	10.59	21.25	8.8	20.4	10.8	9.9	18.4	67.43
B3	3.18	2.78	0.4	0.5	0.6	11.3	81.4	75.35
P1	2.00	1.12	1.3	2.7	3.7	23.6	65.6	39.34
P2	14.90	54.22	13.6	9.2	3.1	2.1	2.9	
P3	4.95	6.48	3.3	3.0	0.6	3.1	78.4	

Percent sediment texture, October 2010, from Thalwegs (T), Banks (B), and Pools (P) spanning a 200m reach

(Clay < 2 µm, Silt 2-63 µm, Very Fine Sand 63-125 µm, Fine Sand 125-250 µm, Medium Sand 250-500 µm, Coarse Sand 500-1000 µm, Very Coarse Sand 1-2 mm, Gravel 2-40 mm)

Lower Santa Cruz, B class reach

	Clay	Silt	VF Sand	F Sand	M Sand	C Sand	VC Sand	Gravel
				0.5km				
T1	0.67	2.90	1.1	2.6	15.1	37.6	40.0	27.77
T2	2.33	3.10	1.6	6.8	22.6	36.5	27.2	26.83
T3	2.00	0.88	1.8	9.7	23.9	34.3	27.3	28.67
B1	5.32	16.57	3.4	3.5	13.3	31.1	26.8	25.89
B2	2.00	3.97	1.7	6.0	14.4	35.0	36.9	49.90
B3	2.00	4.29	2.2	14.1	23.4	29.4	24.6	38.15
P1	3.33	5.84	1.9	5.6	10.1	30.3	42.9	47.77
P2	7.32	20.83	8.6	21.3	13.0	13.8	15.1	13.62
P3	3.33	11.90	10.2	15.3	22.8	21.9	14.6	7.37
				15km				
T1	0.67	0.43	0.3	2.2	15.0	41.0	40.4	18.46
T2	0.67	1.10	0.5	3.7	24.8	39.0	30.1	30.85
T3	0.67	0.56	0.2	2.1	19.1	45.4	31.9	20.96
B1	0.67	1.19	0.6	2.9	31.2	46.2	17.2	4.39
B2	0.67	0.55	0.3	1.4	14.0	47.2	35.9	13.36
B3	1.66	2.98	2.6	5.9	21.9	44.9	20.0	4.78
P1	0.67	0.67	0.2	1.2	25.2	50.5	21.5	11.58
P2	0.67	0.41	0.2	1.6	18.7	57.3	21.2	7.66
P3	0.67	0.80	0.3	1.6	15.0	42.4	39.2	21.57
				25km				
T1	0.00	1.16	0.4	4.1	27.1	32.7	34.5	33.18
T2	0.00	1.29	0.4	3.3	27.8	30.0	37.2	37.45
T3	0.00	2.05	0.4	3.6	33.2	36.8	24.7	18.24
B1	0.00	1.70	0.7	1.6	10.5	41.5	44.3	32.77
B2	0.00	2.34	1.0	4.5	18.1	52.7	21.3	3.52
B3	0.67	2.08	1.9	10.1	43.9	24.2	17.3	8.85
P1	0.33	2.52	1.7	6.6	21.3	46.9	20.6	9.81
P2	6.32	21.12	8.7	16.3	6.6	26.0	14.9	0.35
P3	2.00	6.50	6.0	19.5	48.1	16.2	1.7	0.36

Upper Santa Cruz, A+ class reach

	Clay	Silt	VF Sand	F Sand	M Sand	C Sand	VC Sand	Gravel
				3km				
T1	0.80	0.56	0.3	2.9	20.0	33.4	42.1	39.27
T2	2.67	0.00	0.3	2.9	20.9	46.8	28.1	42.36
T3	2.00	0.24	0.4	4.9	22.8	36.6	33.0	49.04
B1	1.07	0.99	1.8	16.3	35.8	31.4	12.7	16.51
B2	2.67	-0.31	0.3	8.6	42.0	34.2	12.6	10.21
B3	0.00	2.42	1.1	4.5	15.9	39.6	37.1	49.88
P1	1.33	1.04	0.8	7.7	21.7	33.3	34.1	48.22
P2	3.00	0.00	0.3	6.0	30.3	4.0	23.0	20.45
P3	1.60	3.53	4.4	5.6	9.6	29.8	45.5	52.15
				11km				
T1								
T2	1.33	1.49	0.6	3.9	22.4	36.5	33.8	52.25
T3	0.67	1.07	0.5	4.0	23.7	36.4	33.7	47.93
B1	0.67	0.93	0.6	1.2	15.2	59.9	21.5	6.09
B2	0.00	4.05	1.2	3.2	18.9	41.7	32.2	33.52
B3	0.67	1.73	0.6	1.2	5.7	29.0	61.1	43.48
P1	3.33	0.00	0.4	2.3	10.9	39.0	44.8	41.46
P2	0.80	2.24	0.6	2.9	18.9	35.7	38.9	46.13
P3	1.33	2.08	0.5	2.1	20.0	40.0	33.9	47.01
				15km				
T1	1.33	0.83	0.4	3.6	25.7	42.1	26.0	51.12
T2	1.33	0.27	0.3	2.0	15.4	41.6	39.1	41.46
T3	0.00	1.57	0.3	1.5	14.5	39.8	42.3	56.04
B1	0.67	1.17	0.4	1.5	12.6	39.2	44.4	41.08
B2	0.40	2.96	1.3	3.1	12.3	32.1	47.9	36.47
B3	1.33	1.87	0.8	2.5	16.1	39.1	38.4	39.19
P1	0.13	1.61	0.3	0.6	5.6	34.5	57.2	41.30
P2	1.47	2.82	2.0	2.8	11.7	38.7	40.5	14.00
P3	1.46	1.94	1.4	2.6	13.8	35.6	43.2	50.93

San Pedro River

	Clay	Silt	VF Sand	F Sand	M Sand	C Sand	VC Sand	Gravel
				Charleston				
T1	4.33	0.00	0.4	2.2	7.7	34.1	53.0	62.23
T2	4.66	0.00	1.2	6.2	21.9	37.8	31.6	19.35
T3	1.33	3.12	1.5	5.3	15.2	35.0	38.5	68.91
B1	2.00	1.64	0.6	27.8	11.3	28.0	28.6	36.53
B2	5.99	3.89	1.2	7.3	24.7	29.2	27.6	62.99
B3	2.66	2.90	1.2	3.7	11.8	32.3	45.5	70.88
P1	5.00	0.00	2.5	8.5	7.4	25.7	52.8	61.33
P2	3.33	3.02	1.7	4.9	3.4	8.6	74.9	72.58
P3	1.33	1.24	0.6	3.5	17.9	33.6	41.8	45.49
				Lewis Springs				
T1								
T2	14.66	42.19	14.8	17.8	9.1	1.2	0.2	0.42
T3	2.66	2.16	0.8	5.0	17.2	34.3	37.9	37.73
B1	5.33	7.68	1.8	3.7	18.5	37.9	25.1	25.90
B2	2.00	1.85	0.8	4.8	38.7	29.3	22.5	29.60
B3	2.99	5.08	3.1	17.2	41.1	16.4	14.2	21.39
P1								
P2	1.33	1.85	1.1	3.0	17.5	46.2	29.1	8.16
P3	1.97	1.80	1.0	4.7	37.3	26.6	26.7	24.25
				Fairbank				
T1	1.33	0.40	0.4	2.7	16.5	44.6	34.1	11.11
T2	7.36	6.70	2.0	6.8	16.3	30.1	30.8	53.45
T3								
B1	1.67	1.53	1.9	2.7	24.1	54.0	14.2	3.31
B2	7.06	7.51	3.8	10.9	15.3	22.4	33.0	44.95
B3	2.00	4.30	3.7	7.3	9.3	28.4	45.0	45.44
P1	1.33	1.80	1.2	5.5	18.7	35.3	36.2	35.80
P2	2.33	3.74	2.8	5.1	13.4	30.9	41.7	47.39
P3								

Percent sediment texture, November 2010, from Thalwegs (T), Banks (B), and Pools (P) spanning a 200m reach

(Clay < 2 µm, Silt 2-63 µm, Very Fine Sand 63-125 µm, Fine Sand 125-250 µm, Medium Sand 250-500 µm, Coarse Sand 500-1000 µm, Very Coarse Sand 1-2 mm, Gravel 2-40 mm)

Lower Santa Cruz, B class reach

	Clay	Silt	VF Sand	F Sand	M Sand	C Sand	VC Sand	Gravel
				0.5km				
T1	1.66	0.91	0.8	2.9	14.2	34.1	45.5	42.97
T2	2.66	2.09	1.7	6.4	11.0	30.8	44.9	52.16
T3	1.66	0.07	1.4	9.3	20.9	31.6	35.2	38.86
B1	2.65	0.74	0.7	2.4	11.5	35.4	46.3	48.20
B2	1.99	0.17	0.7	3.2	10.8	33.8	49.3	56.29
B3	2.64	4.74	3.7	14.5	26.4	28.8	19.3	33.04
P1	2.65	2.85	0.9	1.4	5.5	35.6	51.0	31.38
P2	4.63	9.94	3.7	7.0	14.5	32.2	28.1	18.99
P3	2.66	8.82	8.7	11.0	6.5	23.0	39.4	28.22
				11km				
T1	1.32	0.00	0.2	1.9	24.3	37.0	35.6	32.75
T2	1.32	0.00	0.1	1.5	27.7	39.8	30.1	27.49
T3	1.33	0.00	0.1	2.3	25.4	32.2	39.6	36.76
B1	2.66	0.00	0.3	3.9	28.9	45.9	19.9	3.98
B2	1.33	0.00	0.4	1.9	10.7	41.7	44.2	30.41
B3	1.33	0.00	0.4	5.4	39.7	37.3	17.0	8.19
P1	8.61	28.59	8.0	12.7	5.3	21.8	15.1	0.91
P2	7.94	23.46	26.8	27.9	9.4	2.9	1.6	0.90
P3	2.65	3.90	3.9	16.5	48.3	23.2	1.3	0.10
				25km				
T1	2.65	0.00	1.3	4.3	34.4	43.4	14.2	3.30
T2	2.66	0.00	0.2	2.6	20.8	43.8	32.1	23.15
T3	3.97	0.00	0.2	0.7	10.0	42.2	46.4	27.89
B1	1.33	0.00	0.1	0.5	10.8	42.1	46.1	26.21
B2	2.66	0.00	0.1	1.3	31.7	50.3	15.9	4.39
B3	0.67	0.65	0.2	0.8	24.6	55.9	17.1	3.08
P1	3.31	0.50	0.9	5.4	37.6	39.5	12.5	2.24
P2	2.65	0.00	0.3	1.2	31.7	51.8	13.4	1.43
P3	2.65	0.00	0.2	0.8	22.7	54.2	20.1	8.52

Upper Santa Cruz, A+ class reach

	Clay	Silt	VF Sand	F Sand	M Sand	C Sand	VC Sand	Gravel
				3km				
T1	1.33	0.96	1.4	9.0	26.0	32.2	29.1	50.36
T2	0.00	3.35	1.4	5.3	19.9	28.1	42.0	67.33
T3	0.33	1.54	1.1	10.3	31.1	35.7	19.9	46.42
B1	0.00	1.97	1.5	1.9	20.2	49.4	24.9	11.48
B2	0.33	1.98	2.3	10.7	27.6	30.4	26.8	26.95
B3	0.33	2.46	2.4	8.1	19.7	33.4	33.6	46.46
P1	0.33	1.89	1.8	3.7	15.3	47.2	29.7	10.15
P2	0.33	1.27	1.2	5.5	20.1	35.1	36.4	19.63
P3	0.00	3.29	3.3	9.9	21.5	36.3	25.7	22.10
				11km				
T1	0.67	1.48	0.6	3.5	19.0	34.6	40.1	52.05
T2	2.65	0.00	0.0	0.2	6.3	36.5	56.9	50.90
T3	2.65	0.00	0.3	1.6	14.3	32.8	49.3	46.70
B1	0.00	0.40	0.1	0.5	7.9	36.0	55.4	47.44
B2	3.64	0.00	0.8	1.3	16.5	58.8	21.3	3.83
B3	2.66	0.00	0.2	0.7	12.7	49.1	36.3	24.41
P1	2.98	0.00	0.3	0.5	5.7	34.7	56.8	35.83
P2	3.91	4.98	3.4	2.0	11.4	46.8	27.3	12.41
P3	2.32	0.00	0.4	1.5	15.6	45.3	36.0	38.20
				15km				
T1	3.00	0.00	0.1	0.6	8.5	34.9	54.9	34.61
T2	1.99	0.00	0.1	0.9	13.9	43.6	40.4	34.86
T3	2.99	0.00	0.3	2.0	13.6	39.3	42.8	44.16
B1	2.98	0.00	0.3	3.2	14.0	32.9	47.9	46.40
B2	1.33	0.00	0.1	1.3	26.7	42.3	28.1	37.29
B3	2.66	0.00	0.1	1.0	21.2	43.1	33.8	59.56
P1	3.97	0.00	0.2	0.2	4.5	45.4	47.9	12.73
P2	2.97	0.92	0.7	0.7	14.6	58.8	21.5	2.78
P3	1.67	1.51	1.2	3.2	10.0	32.3	49.9	43.97

San Pedro River

	Clay	Silt	VF Sand	F Sand	M Sand	C Sand	VC Sand	Gravel
				Charleston				
T1	5.33	0.00	0.7	5.0	9.9	33.4	46.6	59.83
T2	3.00	0.00	0.1	0.8	9.7	43.2	44.8	17.18
T3	4.00	0.00	0.7	1.5	3.4	24.3	66.6	65.45
B1	5.33	0.00	0.2	1.2	6.3	27.0	60.9	43.55
B2	4.00	0.00	1.0	7.3	19.0	39.4	29.7	22.45
B3	4.00	0.00	0.8	6.5	20.3	39.5	29.7	25.86
P1	10.97	3.09	2.2	11.8	19.2	21.4	31.1	67.90
P2	5.33	0.00	0.7	2.1	1.6	6.4	84.3	71.71
P3	4.00	0.00	0.2	0.3	7.3	35.7	54.0	31.66
				Lewis Springs				
T1	4.00	0.20	0.5	4.2	23.4	39.4	28.3	45.92
T2	2.00	0.01	0.2	1.6	28.7	37.4	30.1	19.16
T3	4.36	0.45	1.6	3.9	10.5	26.9	52.2	67.71
B1	9.32	0.00	2.5	10.2	33.3	20.1	12.2	37.88
B2	17.32	22.43	15.4	23.3	15.9	5.1	1.7	3.23
B3	2.67	0.91	2.3	13.4	23.4	27.8	29.4	19.15
P1	5.33	2.27	1.0	5.4	32.1	30.9	22.8	40.76
P2	7.33	4.91	1.5	4.1	13.1	33.9	35.1	40.33
P3	3.33	0.59	1.6	14.6	38.9	33.0	7.7	6.29
				Fairbank				
T1	2.00	0.00	0.2	1.5	17.5	42.0	37.1	17.96
T2	3.33	0.37	1.9	7.9	24.6	33.7	27.9	38.52
T3	7.12	0.73	2.2	3.4	8.3	23.1	55.3	76.32
B1	0.00	1.55	0.1	0.7	18.0	47.3	33.0	11.97
B2	2.67	0.00	0.4	1.6	5.9	36.3	53.6	45.02
B3	5.33	4.20	6.3	10.0	12.6	26.0	35.6	56.81
P1	4.33	4.00	1.1	1.6	18.1	55.2	15.5	6.59
P2	4.00	1.21	1.6	6.4	6.2	22.3	58.3	59.19
P3	5.32	4.35	2.9	9.1	22.6	34.7	23.0	63.23

Percent sediment texture, May 2011, from Thalwegs (T), Banks (B), and Pools (P) spanning a 200m reach

(Clay < 2 µm, Silt 2-63 µm, Very Fine Sand 63-125 µm, Fine Sand 125-250 µm, Medium Sand 250-500 µm, Coarse Sand 500-1000 µm, Very Coarse Sand 1-2 mm, Gravel 2-40 mm)

Lower Santa Cruz, B class reach

	Clay	Silt	VF Sand	F Sand	M Sand	C Sand	VC Sand	Gravel
0.5km								
T1	0.00	3.92	4.10	11.87	26.17	28.64	25.29	0.68
T2	0.00	1.89	0.53	6.47	19.95	31.96	39.25	40.03
T3	1.00	0.73	0.21	4.42	24.24	34.37	35.01	37.62
B1	0.00	1.20	1.36	6.15	31.71	46.71	12.73	0.04
B2	0.00	2.25	1.90	11.12	16.73	27.85	39.99	58.30
B3	0.67	1.27	0.85	11.12	37.36	30.09	18.53	26.60
P1	0.00	0.65	0.28	3.62	28.78	40.70	25.58	0.46
P2	0.33	1.66	0.89	4.76	12.95	37.91	41.53	38.62
P3	0.00	1.50	0.42	4.41	25.78	43.49	24.34	31.32
11km								
T1	0.00	0.71	0.10	2.86	26.30	34.64	35.00	38.75
T2	0.00	0.95	0.14	1.73	15.67	35.30	46.20	54.42
T3	0.00	2.22	0.10	1.78	18.98	32.64	44.28	49.39
B1	0.00	1.14	2.43	5.94	16.78	34.32	38.72	30.48
B2	0.33	1.96	0.16	7.47	15.21	38.31	35.23	55.11
B3	0.00	1.12	0.14	2.75	22.23	36.99	36.77	46.53
P1	0.67	14.15	10.75	16.05	29.10	22.46	6.55	2.60
P2	10.66	44.38	10.16	23.45	6.14	3.67	1.75	0.91
P3	0.00	5.57	3.69	11.91	46.44	29.09	3.10	0.55
25km								
T1	0.00	0.23	0.03	0.60	17.66	43.07	38.28	29.85
T2	0.00	0.24	0.03	0.53	14.69	41.08	43.33	29.30
T3	0.00	0.25	0.03	0.54	10.32	38.19	50.53	13.62
B1	0.67	0.00	0.08	0.77	16.18	48.53	33.95	13.90
B2	0.00	0.59	0.03	0.12	3.56	40.38	55.28	9.71
B3	0.67	0.88	0.55	1.60	29.07	55.19	11.93	8.36
P1	0.00	0.68	0.03	0.16	12.92	45.56	40.50	21.82
P2	0.00	2.80	0.11	1.95	36.19	50.45	8.30	1.06
P3	0.67	6.01	1.52	6.63	29.46	38.45	17.16	5.17

Upper Santa Cruz, A+ class reach

	Clay	Silt	VF Sand	F Sand	M Sand	C Sand	VC Sand	Gravel
3km								
T1	1.66	0.00	0.09	1.97	16.29	34.14	46.09	50.88
T2	2.67	0.00	0.29	5.28	24.68	29.21	39.11	57.43
T3	0.67	0.43	0.44	5.58	30.74	36.98	24.88	37.90
B1	1.33	0.96	1.54	10.90	17.73	26.72	40.72	51.95
B2	1.67	1.93	3.59	19.27	19.43	18.66	35.29	45.03
B3	1.33	0.00	0.10	2.60	23.79	42.08	30.56	18.27
P1	1.80	1.59	1.69	2.67	1.76	12.70	78.01	59.50
P2	0.00	16.09	12.82	22.83	10.05	10.59	27.78	49.81
P3	1.33	1.79	1.98	10.99	32.90	27.44	23.01	44.72
11km								
T1	1.33	0.00	0.13	1.57	16.21	33.98	47.08	46.53
T2	0.67	0.05	0.17	3.35	20.81	32.76	42.09	49.94
T3	0.00	0.41	0.02	0.51	10.80	32.61	55.35	41.92
B1	0.00	1.01	0.09	0.15	2.51	37.91	58.33	15.81
B2	0.00	0.57	0.04	0.37	12.45	42.71	43.37	22.44
B3	0.00	15.45	0.19	1.84	11.70	35.21	35.44	14.58
P1	0.00	1.24	0.12	0.21	4.64	43.30	50.08	24.17
P2	0.00	0.72	0.06	0.41	8.72	38.03	51.72	28.18
P3	0.33	4.92	1.82	2.21	13.75	49.97	26.50	6.33
15km								
T1	0.00	1.21	0.11	1.70	17.93	35.14	43.59	49.14
T2	1.33	1.09	0.25	3.50	18.90	31.88	43.06	46.27
T3	0.67	0.51	0.13	1.25	10.38	38.66	47.97	53.33
B1	0.67	6.62	0.79	2.55	13.09	29.20	46.66	48.70
B2	0.33	3.04	0.20	1.76	18.92	36.55	38.87	41.55
B3	0.00	1.05	0.24	1.39	10.09	41.92	45.32	24.64
P1	1.33	0.41	0.19	0.56	5.65	23.85	67.82	40.70
P2	1.33	2.64	0.14	0.28	6.61	41.67	47.33	23.21
P3	2.67	18.52	5.55	7.26	12.40	25.41	28.15	36.02

San Pedro River

	Clay	Silt	VF Sand	F Sand	M Sand	C Sand	VC Sand	Gravel
Charleston								
T1	0.67	1.45	0.45	4.05	14.82	41.23	37.71	30.98
T2	2.00	3.65	1.01	4.64	6.20	29.92	52.68	21.36
T3	0.00	2.58	0.10	1.32	13.96	30.58	51.52	55.95
B1	1.33	0.12	0.08	1.18	12.91	45.52	39.03	45.99
B2	1.33	1.05	0.81	5.30	13.88	29.80	47.82	49.13
B3	3.16	18.04	2.23	4.06	2.53	15.64	54.39	73.49
P1	2.67	4.62	6.04	13.49	9.59	20.12	43.48	46.30
P2	2.00	2.92	0.25	2.28	11.33	26.79	54.47	51.06
P3	4.00	5.26	2.29	6.13	7.69	24.11	50.49	58.99
Lewis Springs								
T1	1.67	2.64	0.33	1.88	13.97	36.74	42.47	46.19
T2	1.00	0.62	0.15	0.89	30.15	46.53	20.38	17.58
T3	4.00	5.02	1.38	5.53	14.72	26.30	42.94	48.67
B1	1.33	3.17	1.73	9.08	29.38	34.18	20.72	11.92
B2	10.67	24.30	5.80	6.42	12.40	27.81	12.55	9.15
B3	0.00	5.30	1.11	7.90	35.71	35.00	14.75	26.92
P1	2.00	1.70	0.26	1.10	22.61	51.49	20.76	8.14
P2	1.33	2.26	0.23	3.55	35.63	41.05	15.85	3.02
P3	2.00	1.90	0.38	3.58	36.57	35.58	19.96	34.28
Fairbank								
T1	0.33	0.79	0.27	2.61	16.58	38.75	40.77	25.96
T2	1.33	0.32	0.17	0.66	8.66	46.64	42.07	8.90
T3	4.00	4.07	2.82	5.43	9.46	26.19	47.99	48.36
B1	0.67	0.81	0.64	5.08	31.09	39.16	22.15	21.72
B2	1.67	2.67	2.08	7.55	8.17	34.28	43.53	41.50
B3	1.33	1.10	0.38	2.84	19.75	38.58	35.80	39.88
P1	0.67	0.29	0.28	2.58	18.57	36.17	41.20	29.13
P2	0.67	1.35	0.28	2.47	22.43	51.84	20.79	3.48
P3	2.00	31.24	0.81	1.22	3.29	17.65	43.77	42.19